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CORONA DISCHARGE

BY

EARLE H. WARNER

WITH

JAKOB KUNZ

BULLETIN No. 114

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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BY

EARLE H. WARNER

INSTRUCTOR IN PHYSICS

WITH

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ENGINEERING EXPERIMENT STATION

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CORONA DISCHARGE

CHAPTER I

Introduction

1. *Statement of the Phenomenon.*—When high potential differences exist between conductors, the insulating property of the surrounding air partially breaks down, and a conduction of electricity through the air takes place, usually accompanied by a glow at either one of the conductors or in the intervening space. This glow is called the corona. The phenomenon is commonly seen when static machines or Tesla coils are operated in the dark, and less frequently from the tips of lightning rods during an electric storm. The corona is evident at night as it surrounds very high voltage alternating current transmission lines. The conduction represents a loss of power, which on long lines may become an important item. Peek (1), Whitehead (2), and others (3) have carefully studied this phenomenon for alternating differences of potential. In 1912, Peek (4), by a stroboscopic method, showed that there is a difference between the corona discharge from positive and negative conductors. This difference shows that corona caused by alternating potentials is a combination of two effects; and in order to study these effects separately and thus to learn the true facts concerning the phenomenon, continuous potentials must be used. A study of the corona caused by continuous potentials may produce engineering data of value owing to the increasing development of high tension direct-current generation and transmission. Previous to 1914, Watson (5) and Schaffers (6) were the only men who had experimented on the direct current corona.

Because of the desirability of a greater knowledge of the direct current corona, the Physics and Electrical Engineering Departments of the University of Illinois determined to carry out detailed research to develop a satisfactory theory for the corona phenomena. It is the purpose of this bulletin to present the results of the research which has been completed during the last few years.

Note.—The numbers within parentheses refer to the bibliography, page 131.

2. *Acknowledgments.*—The writers desire it to be clearly understood that the research presented in this bulletin is a compilation of the work done by the following, FARWELL, CROOKER, DAVIS, BREESE, OWENS, ANDEREGG, FAULKNER, and WARNER, under the direction of JAKOB KUNZ. The work of these men, as recorded in theses or in published articles, forms the basis of this bulletin. In many instances in order that statements might be accurate the words of the authors have been copied directly.

3. *Apparatus.*—The continuous voltage used in these investigations was obtained by means of a battery of forty, 500-volt, 250-watt, continuous-current, shunt-wound generators connected in series.

These machines are divided into two sets of ten machines each, and one set of twenty machines, each set being driven by a belt-connected, continuous-current shunt motor. The generators are mounted on insulating bases and the shafts of the separate machines are connected by insulating couplings. One terminal of each machine is permanently connected to its own frame in order definitely to limit the electrical strain on the machine insulation to the voltage generated by one armature.

The field of each generator is connected directly across the armature terminals, a single pole knife switch being included in the circuit in order that the machine may either be made to generate or to run idle at will. These switches were operated by means of a hard rubber rod approximately eighteen inches in length, since they may be twenty thousand volts above earth potential. The generators were run somewhat below rated speed in order to limit, to a safe value, the voltage generated without external resistance in the field circuit. The voltage of the machine supplying current to the driving motors was maintained at a constant value by means of a voltage regulator. The constant speed of the driving motors thus produced caused the resultant high potential of the battery of generators to be practically constant. A fine adjustment of voltage was obtained by means of a rheostat in the field circuit of one of the generators. Fig. 1 is a general view of the generating plant.

Most of the experimenters working in this field have dealt with corona in air. Air, however, changes in chemical composition immediately upon the formation of the corona, so that if accurate data are desired within the corona discharge region some arrangement

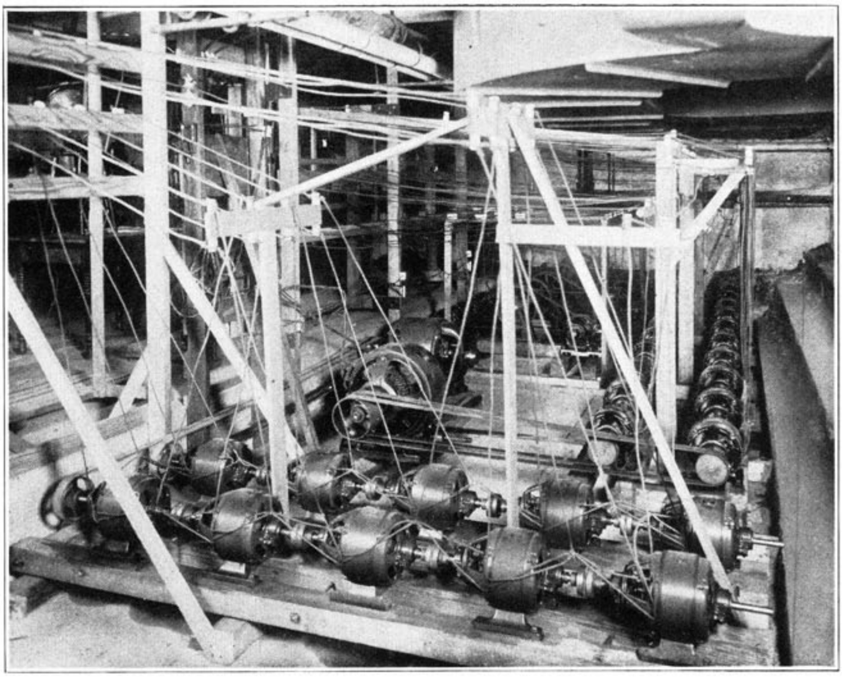

Fig. 1. General View of Generating Plant

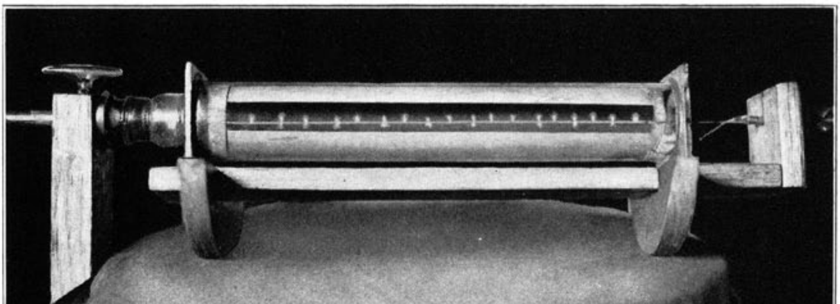

Fig. 2. A Typical Tube, with Slot

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must be made to insure uniformity of chemical structure in the dielectric at all times. Such uniformity is often accomplished by replacing the gas immediately surrounding the conductors as fast as its composition changes. This renewal is often impracticable.

To add to the knowledge of the corona in a substance which probably does not change chemically, experiments have been performed with chemically pure hydrogen as the dielectric. The hydrogen used in this part of the work was produced by the action of hydrone, a commercial alloy of lead and sodium, upon water. The reaction of the sodium with the water produces hydrogen, the lead acting as a retarding agent only. The hydrogen was collected over water and purified as used.

The purifying process consisted in forcing the hydrogen through concentrated sulphuric acid drying bottles placed in series with a calcium chloride tube, and then through a tube in a combustion furnace which contained red hot metallic calcium. The drying agents removed all water vapor and the heated calcium removed all traces of oxygen and nitrogen. Immediately after purification the hydrogen was conducted into the corona apparatus. In the purification of the hydrogen a discharge tube was connected directly to the corona apparatus, and the purity of the hydrogen was tested with a Hilger spectroscope. After careful purification no traces of any other gas than hydrogen were visible in the bright line spectrum.

The type of the corona discharge tube, used in most of the experiments to be described, was a cylinder with a wire strung along its axis. This type of tube was chosen for several reasons:

(1) The corona phenomena, occurring when this type of apparatus is used, lend themselves peculiarly well to mathematical analysis.

(2) The construction, manipulation, operation, and repair of the apparatus are extremely simple.

(3) The field distribution is symmetrical with respect to the wire, and any irregularities in the wire are immediately recognizable in the discharge.

(4) This type of apparatus has been used by other investigators; thus results could be compared with greater assurance of reliability.

The apparatus was so arranged that wires of different sizes could be easily strung and held taut exactly along the axis of the cylinder. In order to limit the length of the wire from which the discharge took place, glass plates with holes for the wire to pass through were sealed to the ends of the cylinder so that the holes were on the axis of the cylinder and metal bushings were inserted in these holes. The wire which was run through the bushings was held taut by sealing wax. The cylinder was provided with a side tube through which the air could be pumped out and dry air or pure gases allowed to enter. When the visible character of the corona was to be studied and photographed, the metal cylinder was provided with a longitudinal slot and the whole tube placed in a glass cylinder. Fig. 2 shows a typical tube with slot.

The voltages, if low, were measured with a Braun type Kohl electrostatic voltmeter, and, if higher, a vertical type Kelvin electrostatic voltmeter, having ranges of 5,000, 10,000, and 20,000 volts, was used. Frequently these instruments were calibrated by means of an attracted disk electrometer. In computing the voltages from the disk electrometer the end correction as treated by Maxwell (7) was applied.

Currents were measured by means of a d'Arsonval galvanometer and an Ayrton universal shunt. These were calibrated as a unit by connecting them in series with a high resistance and a dry cell, the

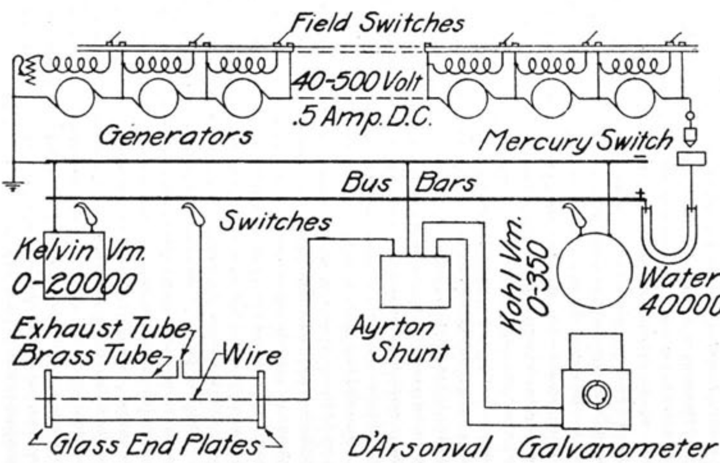


FIG. 3. DIAGRAM OF CONNECTIONS

voltage of which had previously been determined by means of a potentiometer. The voltage of the dry cell was determined both in open circuit and on closed circuit with the smallest series resistance used in the calibration placed in series with the cell. The change in terminal voltage due to the current flowing was, in every case, found to be entirely negligible.

The machines, measuring instruments, and corona apparatus were connected as is shown in Fig. 3. The arrangement of the connections made so that the corona occurs between a positive wire and a grounded coaxial cylinder will be referred to throughout this bulletin as corona with "the wire positive" or as "positive corona." Likewise, when the connections are such that the corona occurs between a positive tube and a grounded wire (as in Fig. 3), the corona will be referred to as corona with "the wire negative" or as "negative corona."

CHAPTER II

General Appearance of the Corona about a Wire in a Cylinder

As the voltage across the corona apparatus is gradually raised, a point is reached when a marked increase in the current occurs, and a further increase in voltage causes the current to increase very rapidly. The voltage at which this sudden increase, indicated by the deflection of the galvanometer, occurs is called the "critical voltage." "Visible glow voltage" means the voltage at which the light about the wire first appears. The visible glow voltage may be identical with, or higher than, the critical voltage.

The positive and negative corona have entirely different appearances and will be considered separately.

4. *Wire Positive in Air.*—For all pressures and sizes of wire used a uniform purple glow surrounds the positive wire. The wire has a tendency to vibrate at high pressures and high current densities as is shown by *a*, Fig. 4. The thickness of the luminous film seems to be a constant for all current densities and pressures, the intensity or brilliance of the discharge only varying with the current and pressure. Positive corona in air at various pressures is shown in Fig. 4.

5. *Wire Negative in Air.*—With the wire negative the appearance of the corona is changed in a very marked degree as is shown in Figs. 4 and 5. From these photographs the following properties can be observed:

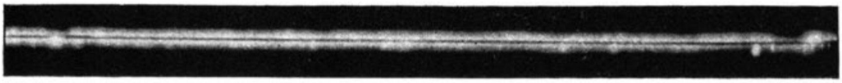
(1) With a constant wire diameter and decreasing pressures the discharge gradually changes from a fairly uniform luminous mass with ragged boundaries to a beady discharge as is shown in Fig. 5. The luminous mass is shown breaking up into beads at *f* and *g*, Fig. 4.

(2) For a constant pressure and decreasing wire radii the fairly uniform luminous discharge gradually changes to the beady discharge, so that for small wires (less than 0.17 mm. in diameter) the beady discharge occurs at all pressures between

(*a*) WIRE +, PRESSURE 747 MM., VOLTS 9110, AMPERES 11.8×10^{-5}

(*b*) WIRE —, PRESSURE 747 MM., VOLTS 8850, AMPERES 12.0×10^{-5}

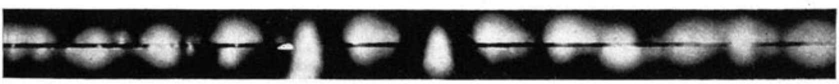
(*c*) WIRE +, PRESSURE 427.0 MM., VOLTS 6795, AMPERES 6.60×10^{-3}



(*d*) WIRE —, PRESSURE 427.0 MM., VOLTS 6350, AMPERES 7.11×10^{-3}

(*e*) WIRE +, PRESSURE 229.0 MM., VOLTS 4680, AMPERES 6.72×10^{-3}

(*f*) WIRE —, PRESSURE 229.0 MM., VOLTS 4265, AMPERES 6.60×10^{-3}



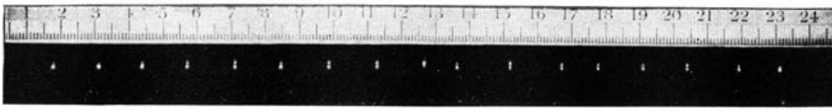
(*g* WIRE —, PRESSURE 87.0 MM., VOLTS 2200, AMPERES 6.70×10^{-3}

(*h*) WIRE —, PRESSURE 46.9 MM., VOLTS 1450, AMPERES 4.33×10^{-4}

(*i*) A. C., PRESSURE 747 MM., VOLTS 8180, AMPERES 6.65×10^{-5}

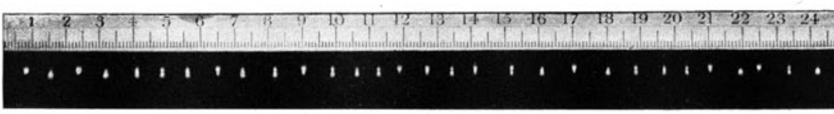
FIG. 4. VISUAL CHARACTERISTICS OF THE CORONA IN AIR

(*a*) Wire —, Pressure 119.3 mm., Volts 2500, Amperes 0.327×10^{-4}



(*b*) Wire —, Pressure 119.3 mm., Volts 2800, Amperes 1.03×10^{-4}

(*c*) Wire —, Pressure 119.3 mm., Volts 3160, Amperes 2.23×10^{-4}



(*d*) Wire —, Pressure 119.6 mm., Volts 3550, Amperes 4.65×10^{-4}

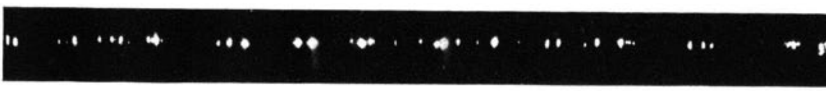
(*e*) Wire —, Pressure 119.6 mm., Volts 3870, Amperes 10.0×10^{-4}

(*f*) Wire —, Pressure 119.6 mm., Volts 4020, Amperes 16.2×10^{-4}

Fig. 5. Variation of the Number of Beads with the Potential Difference

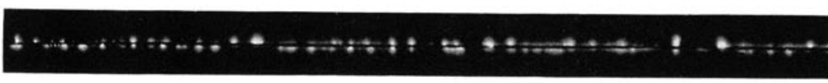
(*a*) Wire —, Pressure 778.0 mm., Volts 3721, Amperes 9.15×10^{-3}

(*b*) Wire +, Pressure 436.0 mm., Volts 3840, Amperes 15.0×10^{-5}



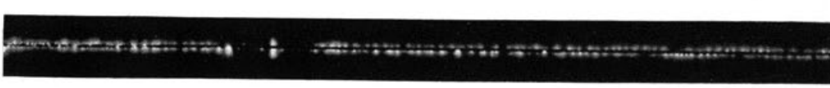
(*c*) Wire —, Pressure 436.0 mm., Volts 2390, Amperes 18.0×10^{-3}

(*d*) A. C. Pressure 436.0 mm., Volts 2710, Amperes 18.3×10^{-3}



(*e*) Wire —, Pressure 391.0 mm., Volts 4585, Amperes 3.57×10^{-3}

(*f*) Wire +, Pressure 234.5 mm., Volts 4500, Amperes 21.3×10^{-5}



(*g*) Wire —, Pressure 234.5 mm., Volts 2025, Amperes 1.76×10^{-3}

Fig. 6. Corona in Hydrogen

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atmospheric and 50 mm. of mercury. Under certain conditions of pressure and voltage these negative beads or brushes distribute themselves uniformly along the wire as is shown in Fig. 5. For the lowest pressures the beads consist of a bright cylindrical core along the wire, this core being surrounded by a narrow dark space and enveloped in turn by a purple glow of relatively large diameter. For increasing pressures the central core contracts to a point on the wire, from which the discharge spreads out fanlike in a plane at right angles to the wire. For still higher pressures the fan seems to close and finally to degenerate to a small brush.

(3) The number of brushes varies with the potential difference. That the number of brushes is a function of the potential difference is shown in Fig 5. Between the voltages at which the arrangement of the brushes was most regular, there seemed to be a transition period in which there were many little brushes in addition to those that were larger. An increase of voltage would then produce a set of full-sized brushes.

6. *Wire Positive in Hydrogen.*—With the wire positive and sizes of wire less than 0.405 mm. in diameter, the wire is surrounded by a thin luminous layer which is essentially uniform, as shown at *b*, Fig. 6. As the size of the wire is increased, this glow becomes more and more irregular. At first there are spots somewhat brighter than others. For a wire as large as 2.59 mm. the discharge takes the form of a large number of brushes similar to the point-discharge in air. It has been impossible to obtain satisfactory photographs of these brushes. They are closely spaced along the length of the wire with a fairly uniform glow between them. The positive discharge is blue in color. If the potential is increased to a high value, a brilliant red spark will pass between the wire and the tube. This spark is followed by a pale blue arc having incandescent blue spots at both ends. These arcs are illustrated in *f*, Fig. 6.

7. *Wire Negative in Hydrogen.*—The typical form of discharge with the wire negative is shown in Fig. 6. For small wires and large pressures the discharge on the wire consists of distinct bright beads with well defined edges, while for large wires and small pressures it changes to a more fuzzy discontinuous discharge. As the potential

is continually increased from values below to values above the critical point, the first evidence of a breakdown of the gas around the wires of small radii is the appearance of an intermittent flickering glow which changes almost immediately with the change of potential to a number of flickering unstable bright spots on the wire. For wires larger than 0.200 mm. in diameter the flickering glow does not form, but the beady discharge is the first to form for these wires. In all cases, however, a voltage increase causes an increase in the number of spots; the corona current gradually increases (a time element enters in the building up of the current) and finally a stage is reached where the spots condense into one brilliant bead. The formation of this bead is accompanied by an extremely rapid increase of current and a correspondingly large and rapid drop in the potential across the tube. A further increase in voltage causes more small bright spots to form, and also causes an increase in the brilliancy of the bead. The newly formed spots condense into a second bead upon a further increase in voltage, and in this manner the number of beads and the current increase as the tube voltage is increased.

If the generator voltage is now decreased, the behavior of the corona is somewhat different. If there are nine beads upon the wire, for example, they will persist but become less and less brilliant until they finally collapse into one or two beads. It seems, therefore, that with increasing voltage the beads appear one by one until the maximum voltage is reached, when the number of beads is also a maximum; but that with decreasing voltage the beads remain on the wire at much lower voltages than those at which they were formed. In fact they persist until a change in number takes place when, not only one but several beads disappear, so that the beads remaining again increase in brilliance, and a considerable lowering of the voltage is necessary to destroy more beads. With a constant number of beads the current increases with increasing voltage. The bead brilliancy increases also with an increase of current. With a change in the number of beads the current value makes a sudden change. This change is approximately proportional to the change in the number of beads.

Opposite each bead for practically all pressures and all sizes of wire used, there is a number of bright spots on the tube. The number of spots varies from ten to twelve for small wires and for small pressures to many hundred for large wires and for large pressures.

For a given wire and a given pressure the number of spots depends upon the magnitude of the corona current. If only a few spots exist, they will be grouped together around the side of the bead nearest the tube, but when the current is large the spots will form a band extending entirely around the tube and of a width of one centimeter or less. These spots vary in color from pale yellow to a milky blue, depending on the pressure, current, and size of wire. With low pressures and large currents these spots may appear as brilliant green fans with yellow spots where they touch the tube. The green color may be due to the brass tube and not to an inherent property of the hydrogen. The presence of these spots at the tube surface seems to indicate an ionizing gradient in this region.

The predominating color of the various discharges through hydrogen is blue, which ranges from a light silver blue to sky blue. The exceptions to this characteristic blue color have been mentioned in the preceding paragraph.

8. *Alternating Current Corona in Air and Hydrogen.*—When an alternating voltage is impressed across a tube filled with air, the discharge seems to be a combination of the discharges with the wire positive and with the wire negative. As would be expected, the beads appear during the half cycle when the wire is negative and the uniform glow appears during the half cycle when the wire is positive. This is shown in *i*, Fig. 4.

When alternating current is applied to a tube filled with hydrogen, the discharge always appears to be very similar to that observed when the wire is negative, as shown clearly in *d*, Fig. 6. The absence of the uniform luminous layer between the beads shows that the characteristic positive discharge is absent; thus either partial or perfect rectification is indicated. The absence of the positive discharge can better be understood after studying the starting points of the positive and negative corona, as shown in the curves which follow.

If the alternating voltage is sufficiently increased the positive corona discharge forms, and finally with a sufficient increase the positive arc is produced. That the arc occurs during the half cycle in which the wire is positive can be verified by two methods. (1) By watching the discharge as the voltage is increased to the arcing value, one observes the first arc to be a reddish color. This is known to be the positive arc. (2) Oscillograms show that the change in current, indicating the start of the arc, occurs from a positive current lobe.

CHAPTER III

The Starting Point of the Corona

For engineering purposes it is important to know the factors which affect the starting point of the visible glow. In air, of a given humidity, the starting point* is mainly a function of two variables: (1) the radius of the wire, (2) the pressure of the air. In hydrogen the first few investigations disclosed the fact that the starting voltages were erratic under apparently similar temperature, pressure, and wire surface conditions. All disturbing elements, except possibly a time element, seemed to be eliminated; so tests were made to determine the effect on the starting voltage of a variation in the length of time elapsing between successive readings. Fig. 7 shows the results of a repre-

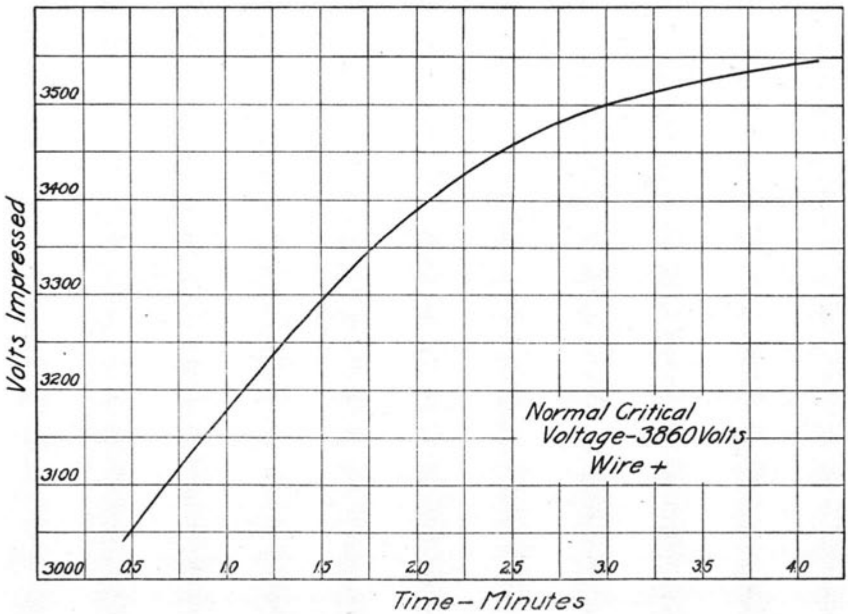


Fig. 7. Variation of Critical Voltage with Time Interval between Opening and Reclosing the Circuit

*The influence of humidity and temperature upon the starting point will be discussed in Chapter V.

sentative test of this type. The method of procedure for taking the readings for this test was as follows: The circuit was closed, corona was started, and the voltage was increased to a value sufficient to make the current reading 2.472×10^{-4} amperes. The circuit was then opened, and the time of opening the circuit was called zero time. One-half minute later the circuit was closed and the critical voltage value was determined as soon as possible. After this determination was made, the current was again brought to 2.472×10^{-4} amperes, the circuit opened and the new time was called zero time. A critical voltage determination was made one minute later. This process was continued until a definite conclusion concerning the variation of critical voltage with time was reached. As a direct consequence of this test all determinations of critical voltages in hydrogen were made only when enough time had elapsed after breaking the corona circuit to insure a resumption of normal conditions.

Experiments were also conducted to determine whether or not the starting voltage was different for the two following cases: (1) when the voltage was gradually increased in value until the critical value was reached, and (2) when the full voltage was suddenly thrown across the tube. No appreciable difference was found.

In addition to this time element the starting point of the visible glow in hydrogen also depends upon the radius of the wire and the pressure of the gas. In the next two sections the variations of the glow voltage with these factors are discussed.

9. *Glow Volts—Radius Curves.*—Fig. 8 gives curves showing the variation of the glow voltages with the radius of the wire when air and hydrogen formed the dielectric. In the air curves the data for points representing wires of very small radii were taken from voltage-ampere curves for silver and tungsten wires. The data for the rest of the points were taken from the characteristic voltage-ampere curves for copper as reproduced in this bulletin. The silver wire used was really silver wire with a platinum core, known as "Wollaston wire." It was used both in its original state, diameter 0.0517 mm., and with some of the silver dissolved off; thus the wires used were of average diameters 0.027 and 0.037 mm. The tungsten wire was that used in 25-watt lamps. The diameters of the very small wires were obtained by the use of a microscope fitted with a stage ruled with parallel lines.

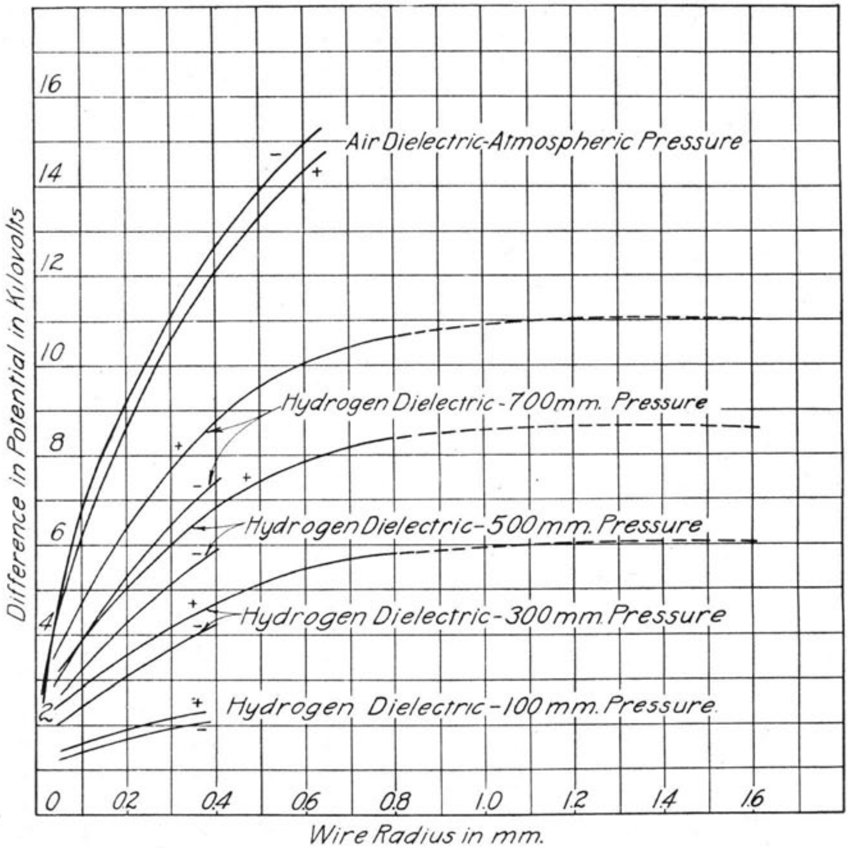


FIG. 8. VARIATION OF THE GLOW VOLTAGES WITH THE RADIUS OF THE WIRE

From the air curves the following conclusions can be drawn:

(1) For the smaller wires, the negative glow appears before the positive.

(2) For the larger wires, the positive glow appears before the negative.

(3) The diameter of wire, 0.075 mm., serves as a dividing line between these two groups. Shaffers has noted similar data which when plotted show a crossing of the curves for the starting points of the positive and negative corona, but he gives 0.01 cm. as the wire radius to separate the two groups. He does

not specify what he considered as the starting point of the negative corona, and it is accordingly not practical to compare his value with that shown in the air curves.

The hydrogen curves show: (1) that the critical voltage for hydrogen is very much less than that for air, (2) that for any particular size of wire and any given pressure the negative starting voltage is much less than the positive voltage. It is seen that for most of the range of wires used the opposite is true for air.

10. *Glow Volts—Pressure Curves.*—Fig. 9 gives curves showing the variation of critical voltages with the pressure. In these experiments only one wire was used when the tube was filled with air but each of two wires was successively used when the tube was filled with hydrogen.

These curves show that in both air and hydrogen for a single size of wire, an increase in the gas pressure requires an increase in the voltage necessary to start the corona discharge. These curves also

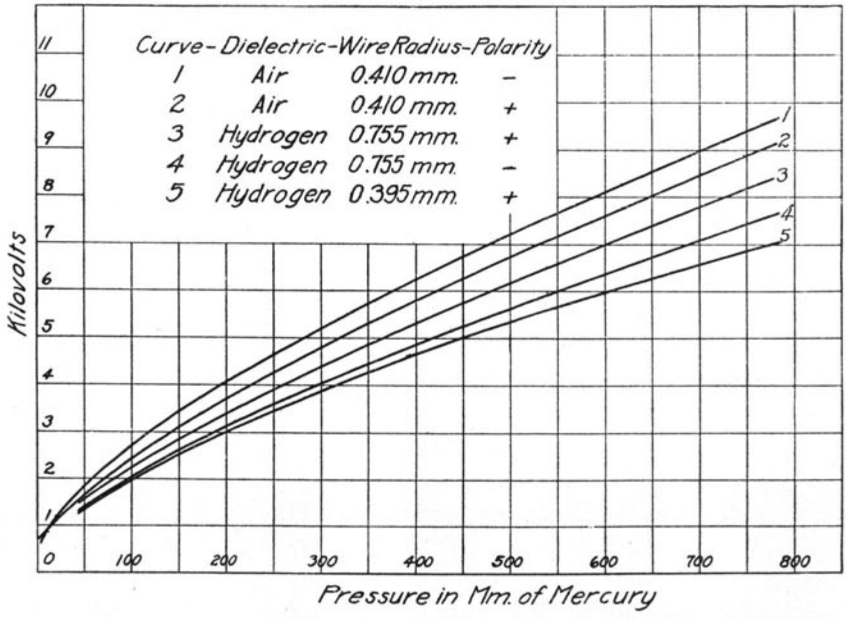


FIG. 9. VARIATION OF THE GLOW VOLTAGES WITH THE GAS PRESSURE

show: (1) that the positive critical voltage for air is lower than the negative critical voltage, while for hydrogen the negative critical voltage is the less; (2) that for a constant pressure and size of wire the critical voltage in hydrogen is much lower than the critical voltage in air.

11. *Starting Point Expressed in Terms of Electric Intensity as a Function of Radius and Pressure.*—The electric intensity, ϵ, at the surface of the wire, subject to a potential, V, coaxial with a cylinder at zero potential, is given by the following equation:

$$\epsilon = \frac{V}{a \log_e \frac{b}{a}} \qquad (1)$$

where a = radius of the wire,
b = radius of the cylinder.

Thus if V, a, and b are known, ϵ can be computed. A sample table showing glow voltage and computed electric intensity as a function of the radius of the wire in air is given in Table 1. While with increasing radius the glow voltage increases, the electric intensity, ϵ, at the surface of the wire decreases. Fig. 10 shows this relation graphically.

TABLE 1

CRITICAL DIFFERENCE OF POTENTIAL TO CAUSE CONTINUOUS GLOW AS FUNCTION OF RADIUS OF WIRE

1 R cm.	2 V+Volts	3 E+Volts per cm.	4 E+Volts Calcul.	5 V—Volts	6 E—Volts per cm.	7 E—Volts Calcul.
0.00135	2720	2.74×10^5	2.62×10^5	2520	2.52×10^5	2.55×10^5
0.002185	3380	2.58	2.29	3230	2.45	2.23
0.0023	3500	2.25	2.09	3300	2.08	2.04
0.00258	3630	2.12	1.99	3500	2.02	1.94
0.00386	4060	1.66	1.67	4060	1.66	1.65
0.00678	5140	1.31	1.34	5320	1.36	1.33
0.00825	5710	1.25	1.25	6140	1.21	1.21
0.012	6600	1.07	1.09	6840	1.09	1.09
0.013	7180	1.07	1.06	7660	1.14	1.06
0.0205	8900	0.93	0.91	9370	0.99	0.92
0.0325	10880	0.80	0.79	11440	0.83	0.80
0.0385	11850	0.77	0.75	12400	0.79	0.76
0.0512	13500	0.71	0.69	14120	0.73	0.71
0.0642	14700	0.65	0.65	15220	0.64	0.64

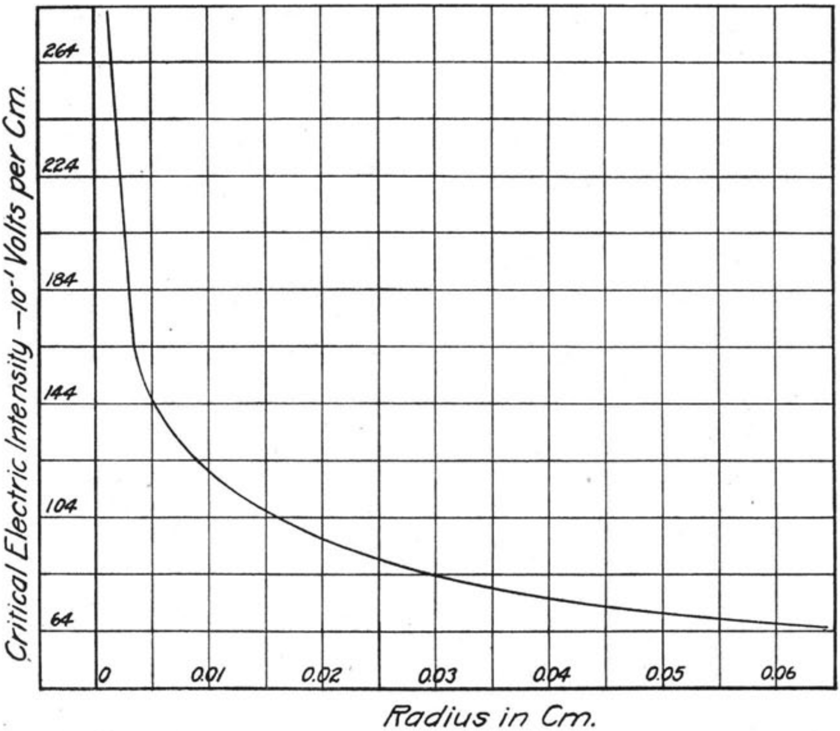


FIG. 10. CRITICAL ELECTRIC INTENSITY AT THE SURFACE OF THE WIRE AS A FUNCTION OF THE WIRE RADIUS

Peek has found that the following law, connecting electric intensity and radius, holds:

$$\epsilon = A + \frac{B}{\sqrt{a}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where A and B are constants and a is the radius of the wire. The data in columns 3 and 6 of Table 1 were obtained by substitution in equation (1) and columns 4 and 7 by substitution in the empirical law represented by equation (2). By comparing columns 3 and 4, and 6 and 7, one sees that for the smallest wires there are deviations from this formula. These deviations occur probably because the critical voltage and the glow voltage differ from each other, and because there is possibly a distortion of the field due to ionization before the glow begins. For the data given it is found that for the positive wire $A = 31.6 \times 10^3$, $B = 8.47 \times 10^3$; and for the negative wire $A = 35.0 \times 10^3$, $B = 8.06 \times 10^3$.

In hydrogen the relation between electric intensity and the wire radius follows equation (2) only approximately, and then only for wires whose radii fall within the limits from 0.1 mm. to 1.0 mm., and for gas pressures ranging from 100 mm. of mercury to atmospheric pressure. For wires of diameters larger than 1.0 mm., the ratio of the radius of the wire to the radius of the tube becomes comparatively small and the discharge phenomena change their character until with a No. 8 wire, 3.23 mm. in diameter, corona does not form at any pressure.

From the curves showing the relation between the critical voltage and the pressure, found by computing the electric intensity, curves could be drawn showing the relation between electric intensity and pressure.

Such curves taken from data with hydrogen can be represented nearly accurately by another one of Peek's formulas.

$$\epsilon = \epsilon_0 \, p + c\sqrt{p} \qquad \qquad (3)$$

where ϵ = critical electric intensity at wire,

p = pressure in percentage of atmospheric pressure,

ϵ_0 and c = constants.

These two laws of Peek can be combined into the one equation:

$$\epsilon = \epsilon_0 \, p\left(1 + \frac{D}{\sqrt{ap}}\right) \qquad \qquad (4)$$

where ϵ_0 and D are constants, and a and p have the significance given to them. For both air and hydrogen it has been found that this law represents the facts only very approximately, especially is this statement true for large wires and low gas pressures. In hydrogen the critical and glow voltages have identical values for all sizes of wire and pressures studied.

12. *Theoretical Considerations.*—Several attempts have been made to give theoretical explanations of the corona discharge. No theory, however, has succeeded in explaining all the phenomena. In many cases the theory of spark discharge has been applied to the corona. Spark and corona are, however, different phenomena. In

the spark there is no distinction between positive and negative; whereas this distinction in the corona is very necessary. In order to start a spark a high potential difference, as a rule, is required; but as soon as the spark strikes, the potential difference falls to a very small value. This is not the case for the corona in air; moreover when the corona is started one has to raise the potential difference a great deal before a spark or rather an arc appears completely across the gas between the electrodes. In the case of the spark the striking potential difference, V, depends only on the pressure, p, of the gas and the distance, d, between the electrodes:

$$V = C\,p\,d$$

where C is a proportionality factor. This law is found by the following consideration. Suppose that there are a few electrons present in the gas in the natural state. If an electric force, $\epsilon = \frac{V}{d}$, is applied, and if λ is the average distance between successive collisions of an electron with a molecule, then this distance, λ, must be such that the force, ϵ, has time enough to impart to the electron the energy, E_c, required to ionize the molecule; hence

$$\epsilon = \frac{E_c}{\lambda} = \frac{V}{d}, \text{ or } V = \frac{E_c}{\lambda}\,d;$$

but λ, the distance between ionizing collisions, is inversely proportional to the pressure of the gas; hence $V = C.\,d.\,p$, or the striking potential difference, V, is constant if $p.\,d$ is constant. The spark depends only on the properties of the gas, especially on the mass of the gas between the two electrodes, but it is independent of the electrodes.

The apparent law of the corona discharge is quite different. The electric force, ϵ, which must be applied in order to start the corona discharge depends not only on the pressure of the gas but also on the radius of the wire approximately according to the expression

$$\epsilon = \epsilon_0\,p\left(1 + \frac{D}{\sqrt{R_p}}\right)$$

or for constant pressure: $\epsilon = A + \dfrac{B}{\sqrt{R}}$

For small wires a relatively strong electric force is required. A later chapter will show that not only the radius of the central wire but also its mechanical and chemical properties affect the initial discharge. At all events in the negative corona it seems as if the electrons were supplied in part by the metal and not only by the gas.

A partial explanation of the last formula can be given as follows: assume that in the neighborhood of the wire in a layer of constant thickness, δ, a certain constant energy is required for the beginning corona, different for positive and negative electricity; in fact the splitting up of the molecules into ions and the emission of light require energy. When a sufficient amount of energy is supplied, the breaking down of the dielectric accompanied by the luminous corona will occur. The thickness, δ, of the luminous layer seems nearly independent of the radius of the wire. In the neighborhood of the wire, the electric force, ϵ, assumes large values so that the polarization is also large and an opposing electric force, ϵ_0, of polarization will be created, so that the resultant electric force is equal to $\epsilon - \epsilon_0$. If k is the dielectric constant, R_1, the radius of the wire, then the energy, E_1, per unit length in a layer of thickness, δ, around the wire is:

$$E_1 = \frac{k}{8\pi} 2\pi R_1 \delta \left(\epsilon - \epsilon_0\right)^2$$

$$\epsilon = \epsilon_0 + \sqrt{\frac{4\,E_1}{kR_1\,\delta}}$$

If E_1, k, and δ are constant, then

$$\epsilon = \epsilon_0 + \sqrt{\frac{4\,E_1}{k\,\delta}}\ \frac{1}{\sqrt{R_1}},$$ the law which approximately represents these observations.

The principle of similarity is now applied to two tubes, T and T'_1, where the linear dimensions are in the constant ratio of $1:z$, so that

$$R'_1 = R_1 z;\ R'_2 = R_2 z;\ \text{then}\ \epsilon_1 = \frac{V}{R_1 \log \frac{R_2}{R_1}}$$

$$\epsilon'_1 = \frac{V}{R'_1 \log \frac{R'_2}{R'_1}} = \frac{V}{R_1\, z \log \frac{R_2}{R_1}} = \frac{\epsilon_1}{z},$$ provided the potential dif-

ference, V, is the same in both tubes. The discharge will start under the same potential difference if $p' = \frac{p}{z}$; then for the mean free paths in both tubes the relation is: $\lambda' = \lambda z$ and for the time intervals, t' and t respectively, between two successive collisions: $t' = t\,z$. At any two corresponding points such as A and A' the electric forces are:

$$\epsilon = \frac{e}{r^2}, \qquad \epsilon' = \frac{ez}{r^2 z^2} = \frac{\epsilon}{z},$$

because it is assumed that at any moment the distribution and movement of the ions in the tubes are exactly similar, but that the total numbers are in the ratio of $1 : z$; hence

$$\epsilon' \lambda' = \frac{\epsilon}{z} \lambda\, z = \epsilon\, \lambda$$

$\epsilon\,\lambda$ is, however, the work done by the electric field during the motion of an ion over a mean free path; if after this mean free

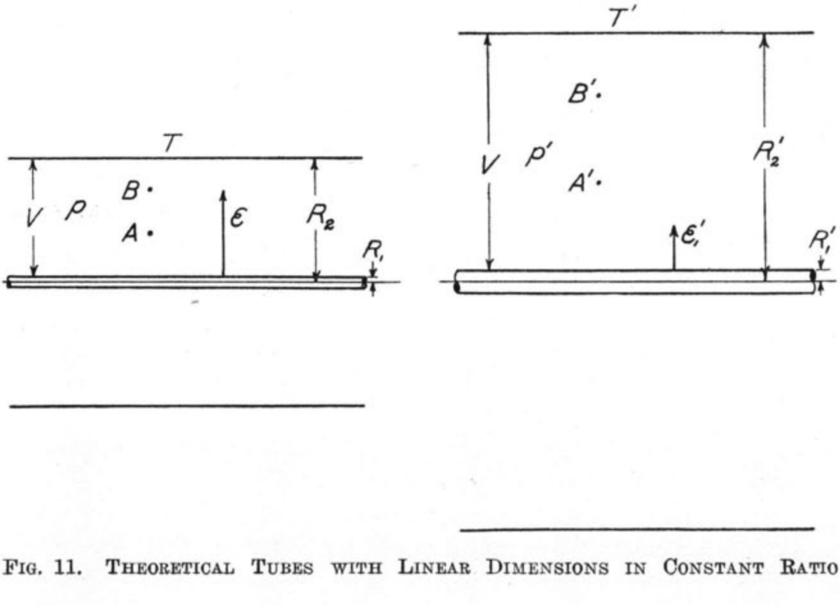


FIG. 11. THEORETICAL TUBES WITH LINEAR DIMENSIONS IN CONSTANT RATIO

path the next collision results in ionization, it will do so in corresponding points of both tubes. Moreover

$$\epsilon'_1 R'_1 = \frac{\epsilon_1}{z} R_1 z = \epsilon_1 R_1 \text{ and}$$

$$p' R'_1 = \frac{p}{z} R_1 z = p R_1; \text{ hence}$$

if $\epsilon_1 R_1$ is kept constant, then $p R_1$ remains constant; or $\epsilon_1 R_1$ is only a function of pR_1. If $\epsilon_1 = \epsilon_0 + \frac{b}{\sqrt{R_1}}$, then

$$\epsilon_1 R_1 = \epsilon_0 R_1 .1. + \frac{b R_1 1}{\sqrt{R_1 .1.}}, \text{ for } p = 1.$$

But if $R_1.1.$ is kept constant and is equal to $R_1 p$, then $\epsilon_1 R_1$ remains constant; hence

$$\epsilon_1 R_1 = \epsilon_0 R_1 p + \frac{b R_1 p}{\sqrt{R_1 p}}, \text{ or}$$

$$\epsilon_1 = \epsilon_0 p + \frac{b p}{\sqrt{R_1 p}}, \text{ or}$$

$$\epsilon_1 = p \left(\epsilon_0 + \frac{b}{\sqrt{R_1 p}} \right),$$

a rule approximately verified at least by experimental measurements in air.

CHAPTER IV

Characteristic Curves

A characteristic curve for the corona discharge shows graphically the relation between the voltage across the tube and the resultant current. Such curves will be considered in the following paragraphs for air and hydrogen at various pressures.

13. *Ampere-Voltage Characteristic Curves for Air at Atmospheric Pressure.*—It was found that the currents flowing, when the voltages were below the critical voltage, were negligible; consequently the following tests were started at a voltage somewhere near the critical voltage. For each voltage the deflection of the galvanometer was read for both polarities of the wire.

The presence of dirt or dust particles on the wire, when negative, has a marked effect upon the discharge. Often a spot or two on the wire would glow long before the wire as a whole was luminous. Because of this fact there is no definite critical voltage as in the positive polarity, for the initial jump of the deflection is much a matter of chance. As the voltage is increased, however, there occurs a critical voltage at which a flickering glow can be seen along the wire preliminary to the spreading of the discharge from a few spots over the whole wire. This phenomenon occurs at a definite voltage for a given size wire and it is this voltage which is given in the tables under "visible glow" for the negative polarity.

Fig. 12 shows the characteristic curves and critical voltage for copper wires of diameters ranging from 0.41 mm. to 1.28 mm.

A study of these data shows the following facts:

> (1) For the smaller wires, the critical voltage is considerably lower than the glow voltage, and a fairly large current exists before a luminous discharge occurs. This statement applies to wire positive.
>
> (2) The smallest wire, for which there is no current for wire positive before glow appears, is 0.135 mm. diameter.
>
> (3) For wires larger than 0.135 mm. diameter, current and glow appear simultaneously, for wire positive.

(4) For wires about No. 26 and larger the current and the visible glow appear simultaneously, as a general rule, for the negative polarity.

14. *Characteristic Curves in Air at Reduced Pressures.*—It was discovered that a change in the pressure of the air in the corona apparatus had a marked effect upon the current caused by a given voltage; thus it was determined to obtain characteristic curves at reduced pressures for different wires. From such data it was hoped that the current readings for the different sizes of wire might be reduced to a 760 mm. basis. A series of characteristic curves was, therefore, taken for different pressures with dry air in the tube. Fig. 13 shows these results for No. 26 copper wire. These curves show a marked increase in the current for a relatively small decrease in

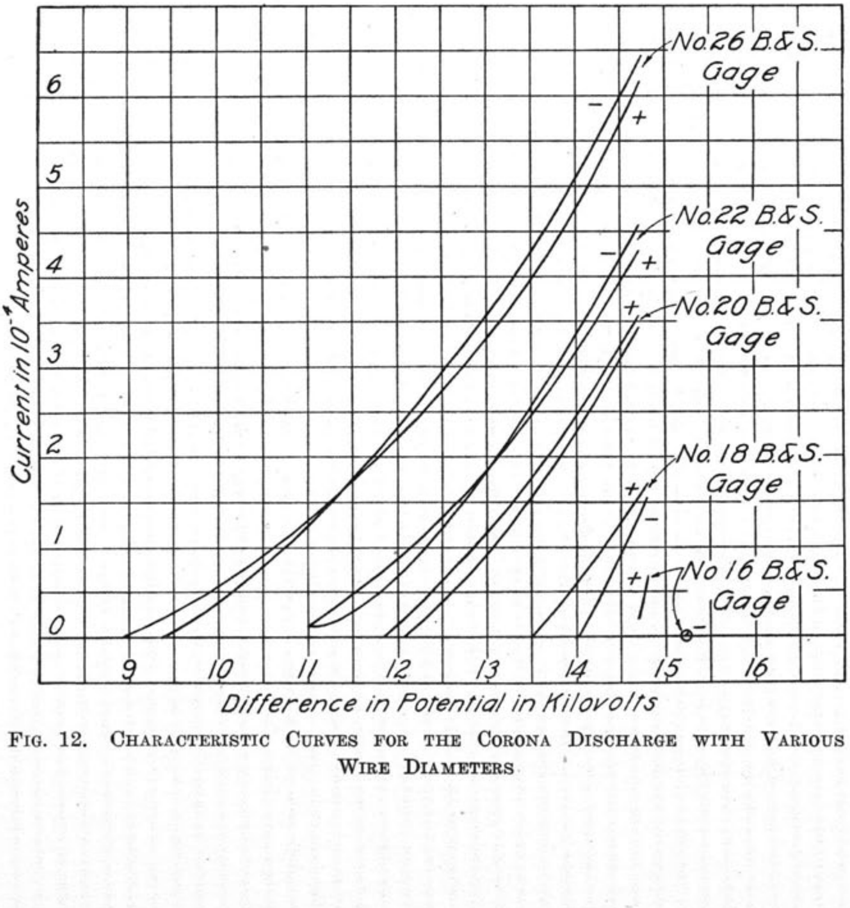


FIG. 12. CHARACTERISTIC CURVES FOR THE CORONA DISCHARGE WITH VARIOUS WIRE DIAMETERS

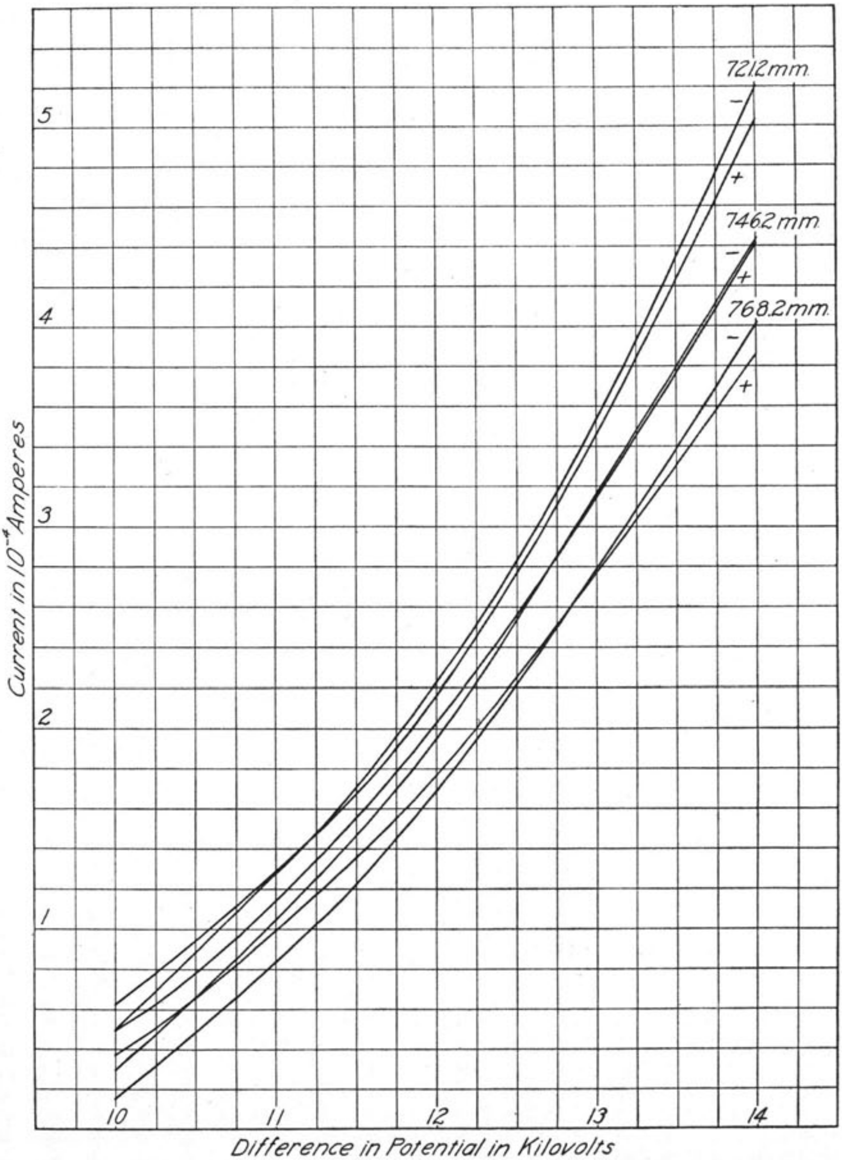


FIG. 13. CHARACTERISTIC CURVES FOR No. 26 B. AND S. GAGE COPPER WIRE WITH AIR UNDER VARIOUS PRESSURES

the pressure. The curves also show an unsymmetrical spacing which suggests the presence of some disturbing factor.

In a number of preliminary experiments it was found to be impossible to repeat observations if the tube was closed and the air not changed. In order to eliminate any disturbing effects due to moisture in the air and possible changes in the constitution of the air in the tube, an arrangement was devised for supplying dry air which could be pumped through the tube out into the atmosphere. The air was dried by being passed through wash bottles containing sulphuric acid and then through a tube containing soda-lime. Fig. 14 shows the results when No. 40 wire was used. These curves show a regular effect of pressure which is larger for the negative than for the positive corona. This regularity seems to indicate that the discordant results

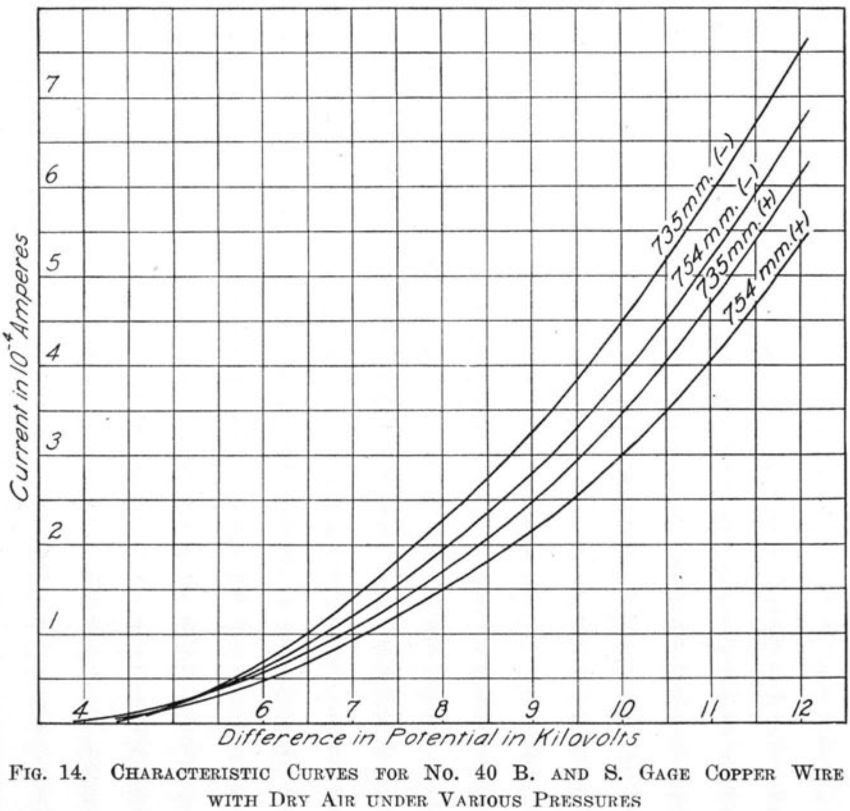


FIG. 14. CHARACTERISTIC CURVES FOR NO. 40 B. AND S. GAGE COPPER WIRE WITH DRY AIR UNDER VARIOUS PRESSURES

obtained in the preliminary experiments were due to the presence of other factors rather than mere change of the pressure.

To determine the effect, if any, of confining air in a closed tube upon the coronal current a series of tests was run under constant pressure with various conditions as, for examples, the closing of the tube, the renewal of the air. The erratic results which followed showed no evident relations and indicated that confinement of the air has a great effect upon the coronal current and also upon the critical and visible glow voltages. Such an effect does not appear strange when one thinks of the ozone, and possibly other products formed which, when the tube is closed, must remain inside and thus change the character of the gas to a considerable extent. It must be concluded from these tests that it is unsafe to compare results obtained in a closed tube with those obtained where there is a plentiful supply of fresh air.

15. *Characteristic Curves in Hydrogen at Atmospheric and Reduced Pressures.*—Some characteristic curves for positive corona in hydrogen are given in Figs. 15 and 16. The most remarkable points about these characteristics are:

(1) The marked difference between the critical voltage and the voltage at which corona ceases.

(2) The difference between the points taken with increasing and those taken with decreasing current.

This persistence of corona at voltages less than that necessary to start the discharge has not been observed with air and continuous potentials.* If there is any such difference for air, its magnitude is certainly very much less than with hydrogen.

This difference between the critical voltage and the voltage at which corona is maintained may be explained by the change in the electric intensity (volts per centimeter) at the surface of the wire after the corona has formed. This change of intensity is caused by the space charge due to the positive and negative ions in the space between the wire and the tube. That such a distortion of the electric field exists will be shown later. The difference between the critical

*See Bennett, A. I. E. E., Proc. Vol. 32, Part II, p. 1796, 1913, for alternating potentials.

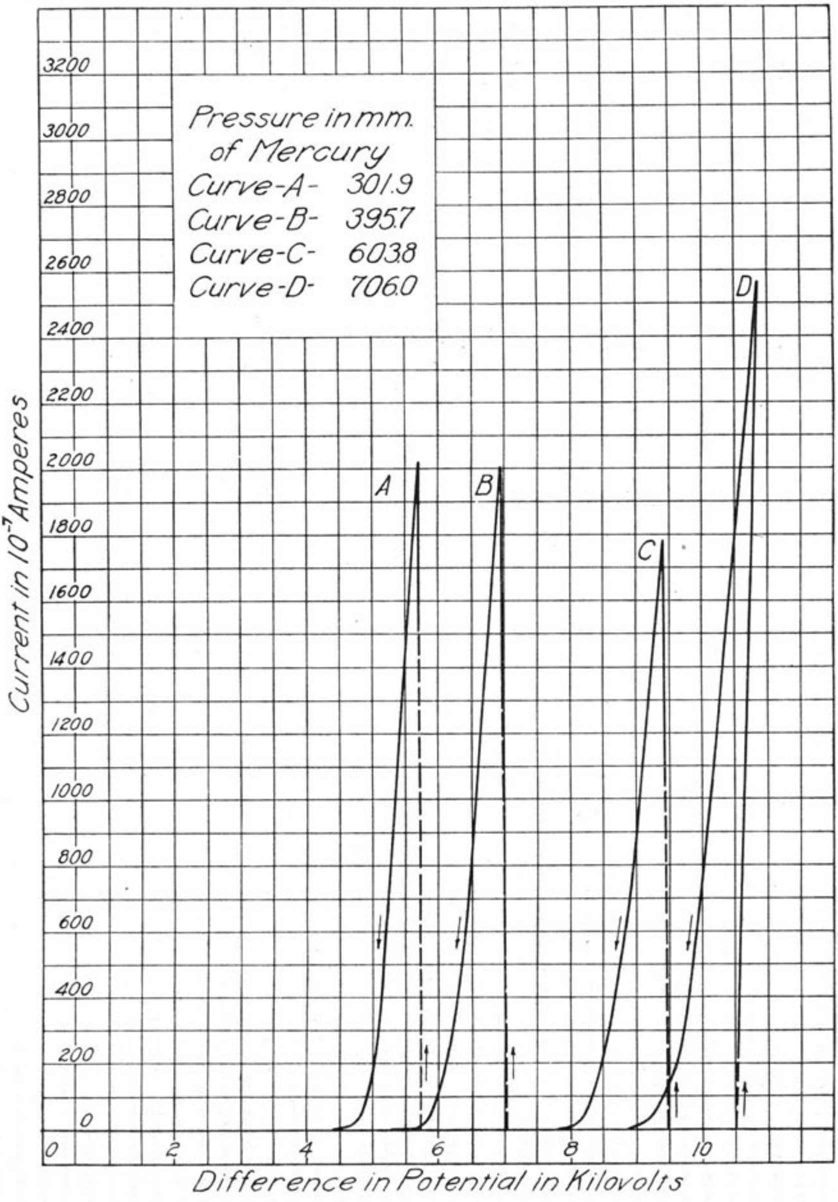


FIG. 15. CHARACTERISTIC CURVES FOR NO. 14 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE +

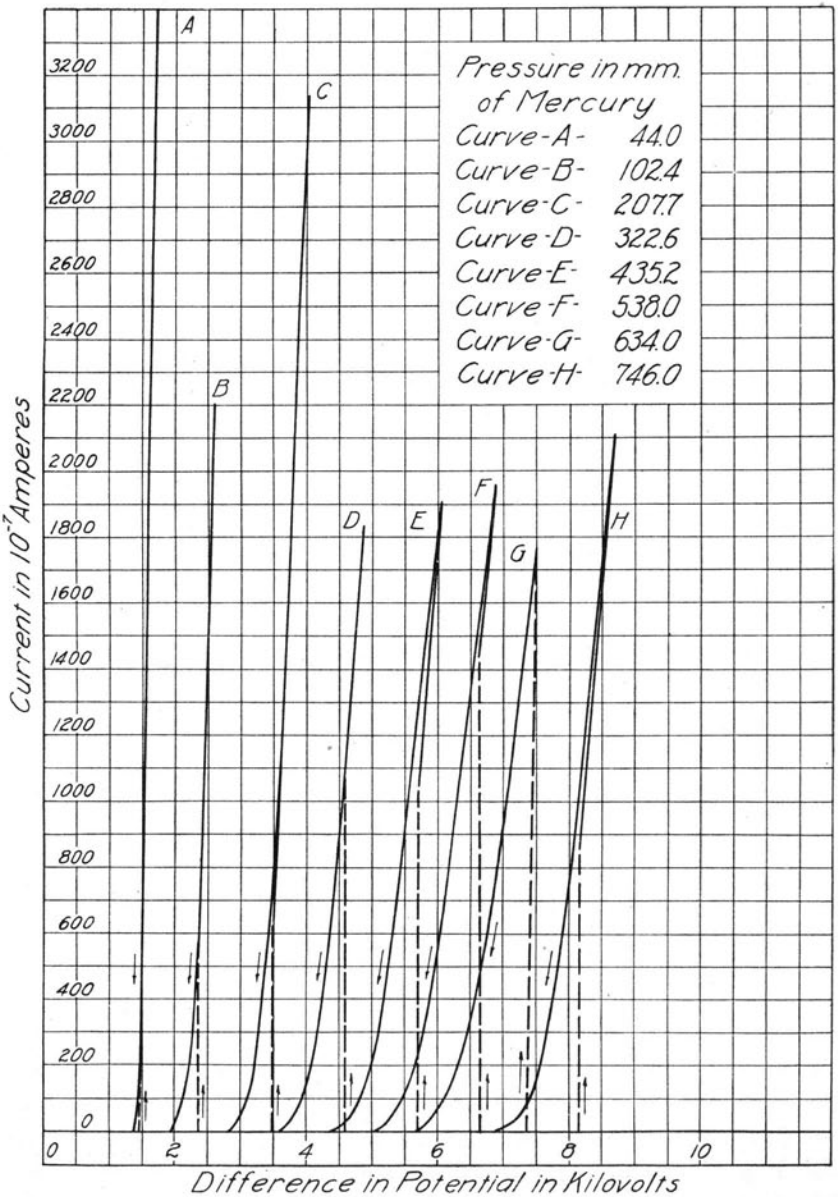


FIG. 16. CHARACTERISTIC CURVES FOR No. 20 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE +

voltage and the voltage at which the discharge ceases is not detected unless all sources of irregular ionization, such as rough spots on the wire, high intensity where the wire passes through the glass, etc., are eliminated.

Other properties of the characteristic curves are:

(3) For a given voltage the current increases with a decrease of density of hydrogen.

(4) For a given voltage the current increases with a decrease in wire diameter.

(5) The characteristic curve is very nearly parallel with the current axis so that a small change in potential produces a very great change in current.

(6) As soon as the copious ionization stage is reached, the current rises to a high value. For wires as large as No. 8 the current increases immediately to arcing values. As the size of the wire is decreased the initial jump diminishes until with a No. 32 wire (0.200 mm. in diameter) at atmospheric pressure the current rises to a value of the order of 10^{-4} amperes.

(7) With a single size of wire and varying pressures, the initial current rise diminishes with a decrease in pressure.

Characteristic curves for negative corona for various pressures and two sizes of wire are given in Figs. 17 and 18. The full line curves represent stable conditions and a constant number of beads. The number of beads on any particular curve may be determined by noting the small number adjacent to the curve. In the small wire it will be noticed that the shape of these characteristics depends to a large extent upon the gas pressure.

With the smaller wire (No. 36 diameter .0121 mm.) the corona seemed to start in each case with a number of very small bright points on the wire. Usually, however, the negative corona started with an unstable flickering glow along the wire. With an increase of voltage the current gradually increased until a point was reached where the small bright spots combined into one negative bead of the kind described in Chapter II. This change in formation was accompanied by a large increase in current and by a drop in the potential difference between the wire and the tube. This drop in potential difference across the tube was, in a certain sense, due to the resistance

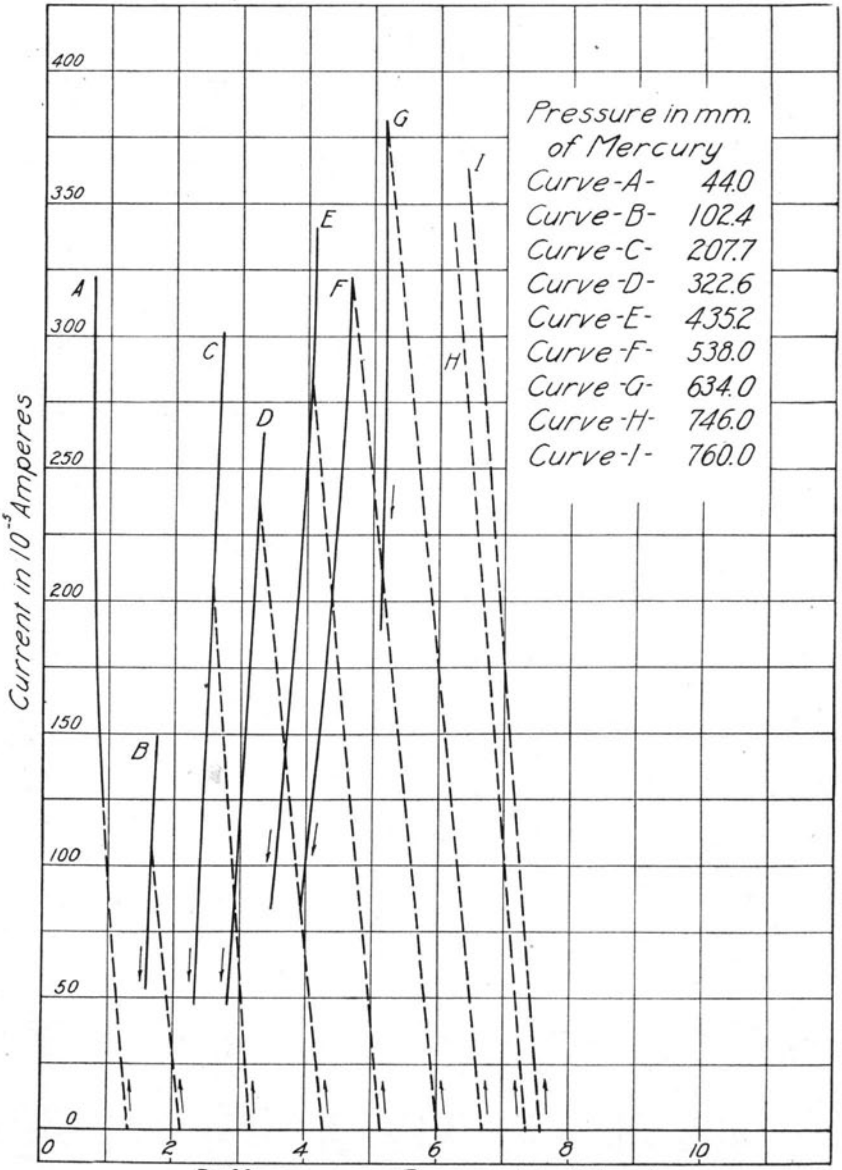


FIG. 17. CHARACTERISTIC CURVES FOR NO. 20 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE —

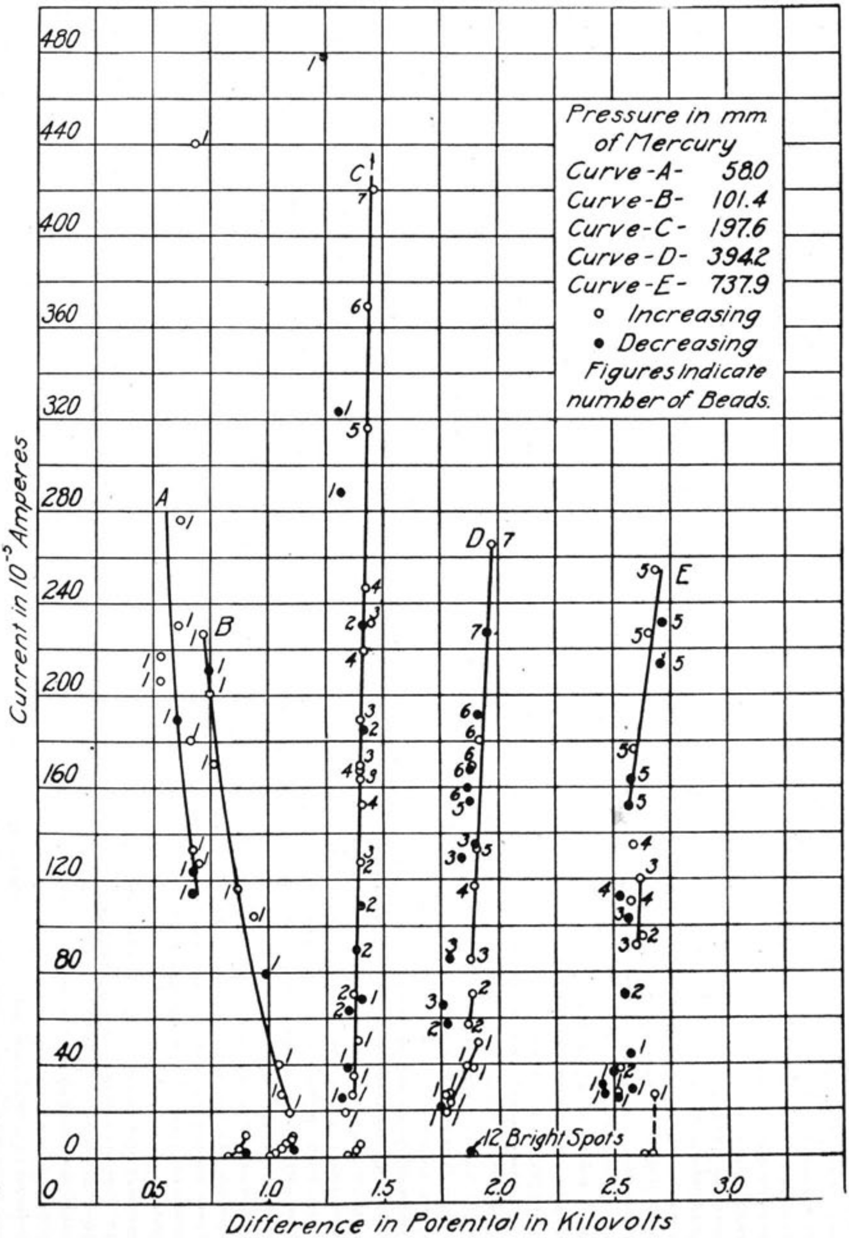


FIG. 18. CHARACTERISTIC CURVES FOR NO. 36 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE –

in series with the corona tube. The increased current taken by the tube causes a higher drop through the series resistance. This increased drop stabilizes the corona discharge and prevents the indefinite increase of current which might result if there were no resistance in the circuit. The gaps in the curves represent unstable conditions. An increase in the generated voltage caused an increase in the corona current, which was accompanied by either an increase or a decrease of the voltage between the wire and the tube depending on the size of wire and the gas pressure.

It may be noticed that for the lower pressures the characteristics are similar to the usual arc characteristic. The discharge, however, was not that of the arc. The arc formed if the machine voltage was sufficiently increased. This increase was accompanied by a further drop in the voltage between the wire and tube and an entire change in the general appearance of the discharge.

The study of the negative characteristics leads to the following conclusions:

(1) For larger wires the curves for a constant number of beads have positive slopes at all pressures above 100 mm.

(2) For a given wire and gas pressure the curves become more nearly parallel with the current axis as the current increases in value.

(3) For a given number of beads and a constant pressure the maximum possible voltage variation is approximately a constant, whatever the number of beads.

(4) With a constant radius and a decreasing pressure the curves revolve in a counter-clockwise direction about their lower points until their slopes change from positive to negative values. The discharges become unstable at the point of infinite slope and resemble the arc discharge in so far as this property is concerned.

(5) With a constant pressure and decreasing radius the critical electrical intensity decreases, and the slopes of the curves approach negative values.

(6) In all cases, as the voltage is gradually increased through the critical value, the beads form one by one, the current values at any time being approximately proportional to the num-

ber of beads. The initial current values never became excessive as they do with the positive corona discharges.

(7) For a given voltage the current increases with a decrease of gas density and also for a decrease of wire radius.

(8) The greater the number of beads on the wire the greater the current change per unit change of potential.

(9) For all but the smallest wire studied the first corona discharge takes the form of beads. For the smallest wire the first discharge at pressures below 200 mm. of mercury takes the form of a flickering unstable glow traveling along the wire. This glow condenses to small, flickering, and unstable beads upon a slight potential increase. These flickering beads persist until currents of the order of 10^{-4} amperes are obtained; then they condense to the ordinary bead discharge.

CHAPTER V

ADDITIONAL FACTORS AFFECTING THE STARTING POINT AND THE CORONA CURRENT

The characteristic and starting point curves show the effect upon the corona current of varying the radius of the wire and the pressure of the gas. In addition to these the following variables also affect the current.

16. *Moisture.*—The effect of moisture has been studied only when air was the dielectric. An arrangement was devised whereby air could be drawn from the room through the tube. The humidity of such air was given by calculation from the readings of wet and dry bulb thermometers. Parallel sets of readings of the current flowing when dry air was pumped continuously through the tube and when air from the room was sucked through before each reading were taken from day to day. The results are shown in Fig. 19. These curves indicate a regular effect due to moisture, with a tendency for the decrease of current by humidity to be greater for negative polarity of the wire. The decrease of current by the presence of moisture is well known; so these results agree with present knowledge.

To determine whether the presence of moisture in the air has an effect upon the critical voltage, a test was run as follows under a pressure of 736 mm. and humidity 68.5 per cent. Air was drawn from the room through the tube, and the voltage was noted at which the initial jump of the galvanometer occurred for wire positive. The positive glow voltage and the negative glow voltage were then determined. Then dry air was pumped through the tube and the same measurements were taken. The results were:

	Wet Air	Dry Air
Positive critical voltage	4300	4190
Positive glow voltage	4350	4260
Negative glow voltage	4275	4370

The effect of moisture apparently is to raise slightly the starting point of the positive corona, but the reverse is true for the negative polarity.

The appearance of the discharge is also affected by moisture, when the wire is negative. With moist air in the tube, the discharge begins with dim spots, and the discharge is of no clearly defined nature, being a mixture of sections of continuous glow and bright spots which are immobile.

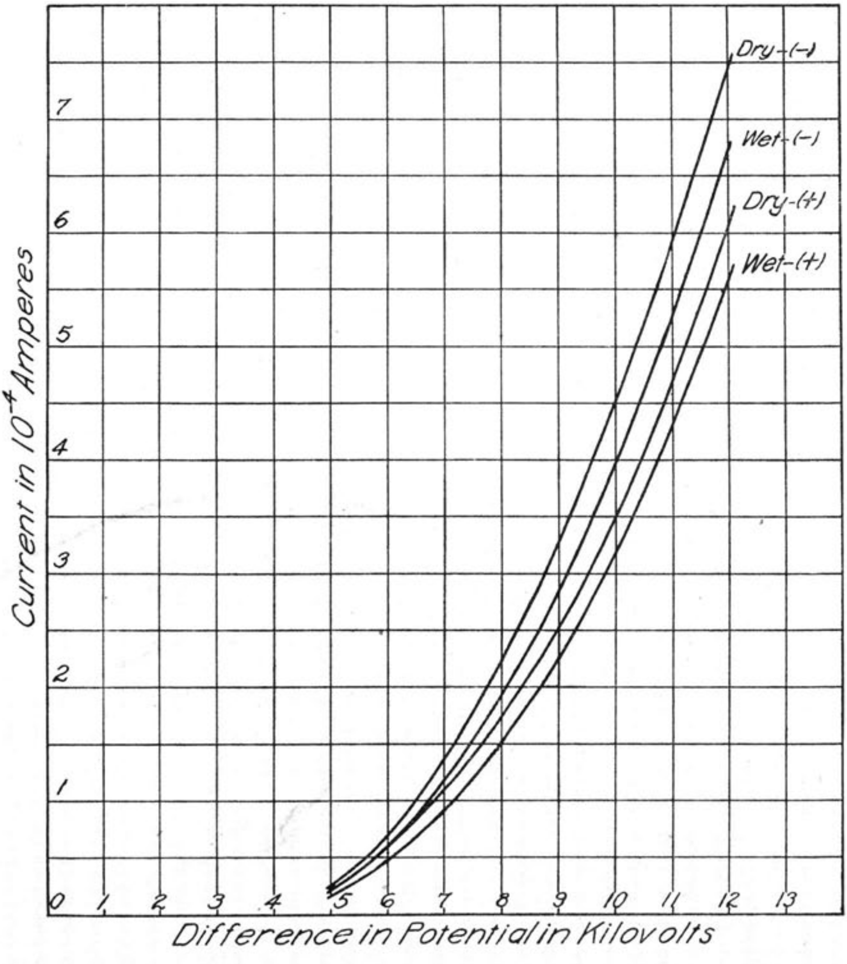


FIG. 19. EFFECT OF HUMIDITY UPON THE CORONA CURRENT

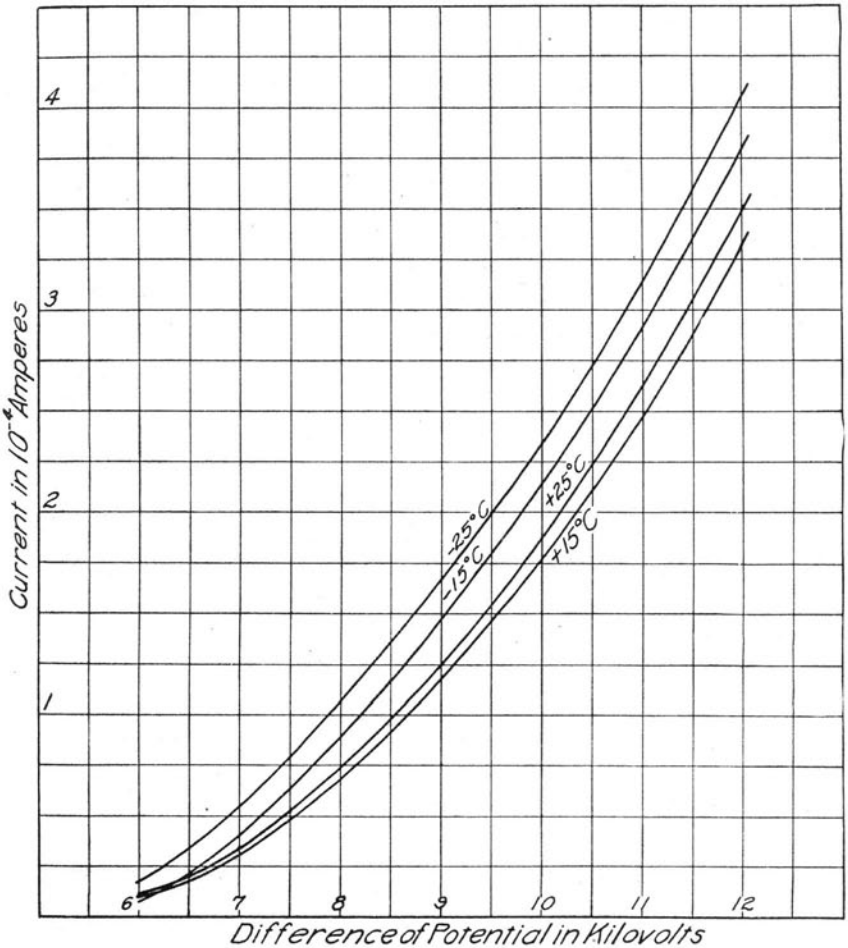


FIG. 20. INFLUENCE OF TEMPERATURE UPON THE CORONA CURRENT AT A CONSTANT PRESSURE OF 760 MILLIMETERS

The effect of moisture on the appearance of the negative discharge was shown by the following experiment: The tube was filled with moist air, and a voltage somewhat above the critical value was impressed. A mixed discharge resulted as was described in the preceding paragraph; then a current of dry air was started through the tube, and little by little the discharge cleared up and resolved itself into a line of uniformly spaced brushes which were in continual agitation. When moist air was again admitted, the discharge resumed its former character.

With moist air in the tube and a fairly high potential difference the wire vibrates circularly for both polarities, and describes a torpedo-like figure of revolution. The filling of the tube with dry air diminishes considerably the amplitude of the vibration for wire positive and stops the vibration entirely for wire negative.

17. *Temperature.*—The influence of temperature upon the current for a No. 36 copper wire in a closed tube under a pressure of 760 mm. was determined for the temperatures 15 degrees C. and 25 degrees C. The results appear in Fig. 20. The lower temperature was obtained by placing cloths wet with alcohol upon the tube and directing a stream of air from a fan upon it. The curves indicate that this difference of temperature makes a far greater difference in the current for wire negative than for wire positive, both currents showing an increase for higher temperature as might be expected.

18. *The Nature of the Surface of the Wire and the Metal of the Wire.*—The fact that the starting point of the negative corona was influenced by dust particles on the wire suggested that a careful study should be made of the corona from different surfaces and from different wires: It was decided to use wires having polished, corroded, and mechanically abrased surfaces. The results will be shown in the following paragraphs:

(1) In the preparation of the polished surfaces care was taken in choosing wires without kinks or surface scratches. These wires were polished with fine emery cloth and finished with chamois and jeweler's rouge just before they were placed in the tube.

The abrased surfaces were prepared by rolling the wire in emery powder between two hard plane surfaces. Care was taken to have the surfaces abrased uniformly over the whole length.

The corroded surfaces were prepared by different methods. The surface of the steel wire was corroded by a solution of nitric acid, which made a black surface. The aluminum wire was corroded by allowing it to remain in a solution of sulphuric acid for a few days. The result was a thin white coating. For copper it was necessary to oxidize the surface by passing a heating current through the wire in the presence of oxygen. Since ozone is produced by the corona discharge in air, the silver wire was coated with a layer of silver peroxide by allowing the corona to play on the wire for some time.

(2) The results of starting voltages for different surfaces and wires are shown in Table 2.

TABLE 2

COMPARISON OF STARTING VOLTAGES FOR DIFFERENT SURFACES AND WIRES
All wires about 0.41 mm. diameter

Polished			Abrased			Corroded		
Press. mm.	Wire − Volts.	Wire + Volts.	Press. mm.	Wire − Volts.	Wire + Volts.	Press. mm.	Wire − Volts.	Wire + Volts.
				COPPER				
50	1 700	1 780	53.2	1 680	1 820	50.3	1 650	1 660
252	2 650	2 600	253	2 550	2 800	250	2 010	2 500
731	6 010	5 760	743	5 600	6 200			
				STEEL				
51.6	1 710	1 710	52.2	1 690	1 740	52.3	1 750	1 700
252.4	2 600	2 600	253.2	2 770	2 770	252	2 550	2 710
727.6	5 660	5 960	736	4 560	5 830	739.4	4 810	5 760
				ALUMINUM				
50	1 760	1 720	52	1 660	1 800	51.9	1 240	1 690
251	2 820	2 900	251.5	2 490	2 900	252	2 370	2 660
741.1	5 880	6 180	741	5 010	5 800	745.3	4 680	5 880
				SILVER				
53.2	1 850	1 820	52.3	1 730	1 740	52.5	1 850	1 780
252.1	3 150	3 050	252.2	2 600	2 900	252.2	3 150	3 000
744.8	4 210	6 130	743.2	5 060	5 850	746	5 760	6 320

The results shown in this table can be discussed for each of the surface conditions of the wire, and for each condition three pressures will be considered.

(3) The general appearance of the corona is the same for all polished positive wires and differs only slightly for negative wires at different pressures. At pressures of nearly 50 mm. when the potential is brought up to the glow potential, wire positive, a very faint flashing glow appears over the whole length of the wire and becomes uniform and steady as the potential is raised slightly. The potential may be carried up to the arcing point without changing the gen-

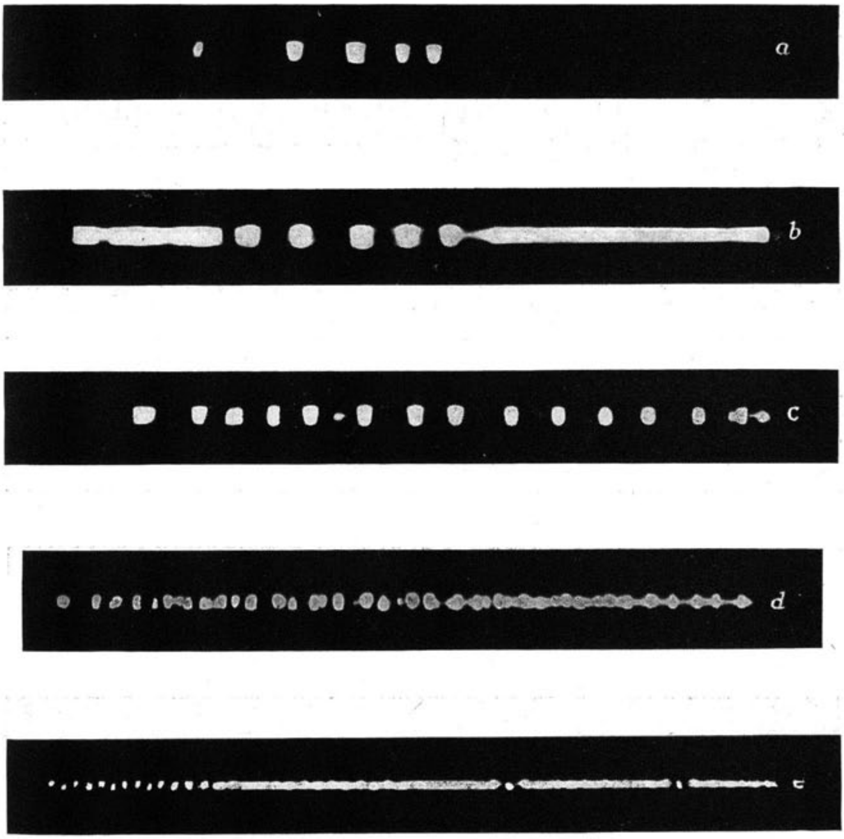
eral appearance of the uniform glow. The only noticeable change is an increase in the brightness of the bluish glow.

For pressures of 50 mm. and for negative wire, the first appearance of the corona is a flashing glow, similar to that for positive wire but of much greater diameter and brightness. Increasing the potential causes this glow to remain steady on the wire, to become uniform and to be very bright. Very little current flows until a stage is reached not far above the starting point, where the bright uniform glow breaks into large, clear, characteristic, negative beads. The current then increases rapidly with the potential. As the potential is increased the beads increase in number but remain large and well defined.

For the polished surfaces and with a pressure of 50 mm. the negative corona on copper begins at a lower potential than the positive. Corona appears at the same potential for both polarities in steel, but for aluminum and silver the positive glow begins at the lower potential. Table 2 shows no general law. With the exception of the silver wire at a pressure of 746 mm. the starting potential for the corroded wire is smaller for both polarities than for the polished wire. For the negative abrased wire the starting point is in general lower than for the polished wire with only two exceptions. With the exception of silver the starting point of the abrased positive wire is higher than that of the polished wire. With increasing pressure the differences involved by abrasion and corrosion diminish. The largest influence is found for aluminum wire, negative corroded at 51 mm.

For pressures of nearly 250 mm. the glow for wires positive is the same as for pressures of 50 mm., being uniform and increasing in brightness as the potential increases. For wires negative and polished it is almost impossible to break the glow up into clear-cut beads at this pressure. With increasing potential the glow becomes brighter and condenses at certain ill-defined points, apparently attempting to form beads, but these condensed regions move rapidly back and forth along the wire.

For atmospheric pressure, wires polished and positive, the glow appears faint but uniform and increases in brightness as the potential is increased. For negative wires a faint flashing glow appears at break-down potentials and increases in brightness with the potential increase. A very few scattered beads form at times, but they are small and unstable with very rapid lateral motion. This motion

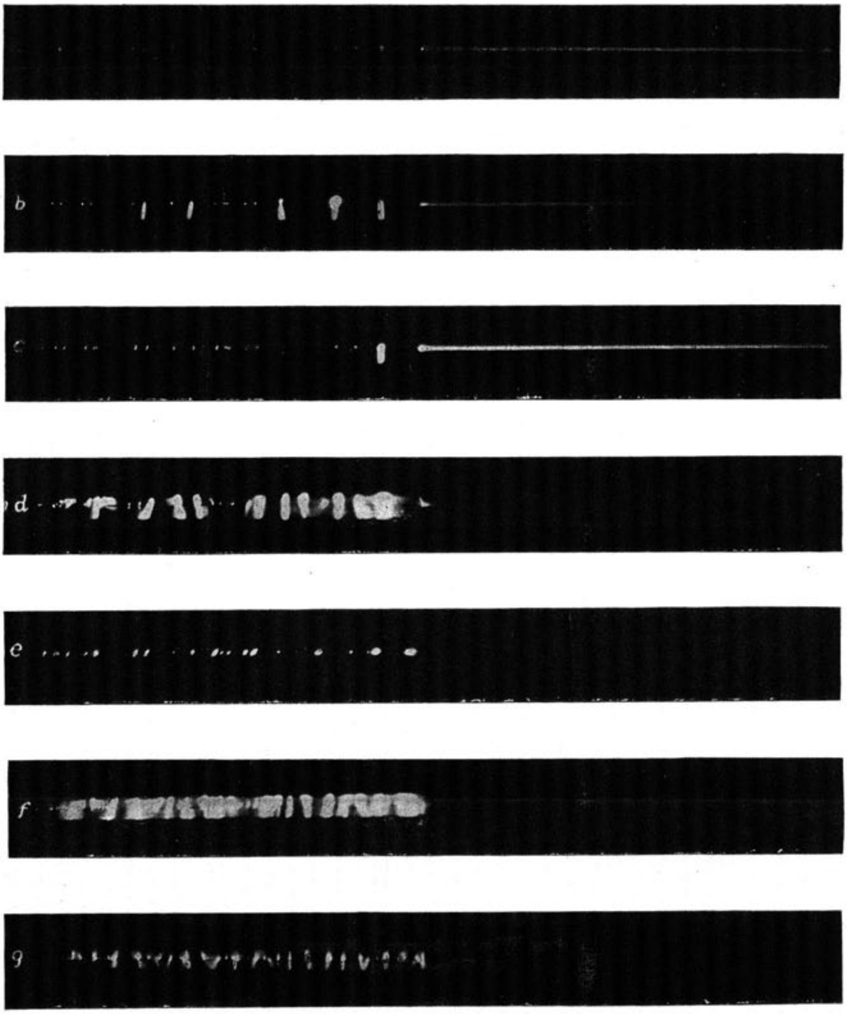


Abrased Polished Corroded

Steel Wire, 0.28 mm., Diameter
All Wires Negative

	Voltage	Pressure
a	990	21 mm.
b	1080	25 mm.
c	1400	39 mm.
d	2300	68 mm.
e	8900	370 mm.

Fig. 21. A Comparison of the Glow on Abrased, Polished, and Corroded Surfaces of Steel Wire



Enameled Polished

German Silver Wire, 0.65 mm., Diameter

		Voltage	Pressure
a	Wire +	1460	23.5 mm.
b	Wire +	1700	25.5 mm.
c	Wire +	1830	35.5 mm.
d	Wire +	2800	91.5 mm.
e	Wire −	3920	185.5 mm.
f	Wire +	4400	185.5 mm.
g	Wire +, Arc in Series	4450	185.5 mm.

Fig. 22. A Comparison of the Glow on Enameled and Polished Surfaces of German Silver Wire

increases in amplitude and speed with increasing voltage. Clear cut beads over the whole wire are impossible here as in the last case.

(4) With wire surface mechanically abrased or roughened and pressure of 50 mm., the positive glow begins with faint flashes as with the polished surfaces; then becomes steady and uniform and increases in brightness as the potential is increased. The starting glow voltage is in general higher than for the positive polished wires, and is also higher than for the abrased negative wires. For wires abrased and negative the corona begins with bright flashes of a fuzzy glow, part of which may have one or two large flashing beads. This flashing glow seems to pulsate in synchronism with the impulses of the driving machinery. A slight potential increase above the first noticeable glow causes the glow to break into well-defined beads which soon become steady and clear and which increase in number with a potential increase. The negative starting voltage for abrased wires is lower than for the polished surfaces.

For wires abrased and pressure of 250 mm. the positive visual glow is the same as for pressure of 50 mm. The positive starting potential is in general higher than for the negative abrased and also positive polished surfaces. The negative glow voltage causes very faint "spears" or small brushes of light to flash from sharp points here and there on the rough surface. These spears increase in size and number with increased potential, some being much brighter than others. As the potential is increased these spears unite into definite, clear beads which at times may be very steady and at other times may have more or less violent lateral movements. The negative starting voltage for abrased surfaces is much smaller than for the polished surfaces.

At atmospheric pressures the positive glow on the abrased wire surfaces usually begins with a few small flashing purple streamers or brushes extending from the wire almost to the tube. These streamers are similar in appearance to the positive fans and to the streamers emitted from the surface of the enamel covered wire, Figs. 21 and 22. These streamers increase in brightness and are accompanied by a soft glow as the potential is increased. After a certain increase in the voltage has taken place, these streamers disappear and only the uniform glow remains and increases in brightness.

For the abrased negative wire at atmospheric pressure the corona starts with small flashing spears the same as for the abrased wire at

250 mm. These spears increase in number very rapidly with an increase in voltage, some of them collecting, so to speak, into small bright beads and then breaking up again. As the potential continues to increase, the beads become more steady and definite, so that at times the abrased wire may be covered with many small, bright, steady, and evenly spaced beads.

(5) The positive visual corona for corroded surfaces is essentially the same for all pressures as has been described for the abrased surfaces. At low pressures it begins with a faint flashing glow which becomes steady and uniform and which increases in brightness. At pressures of 250 mm. the appearance is the same as described for the abrased surfaces, and for atmospheric pressure the corona may start with the small purple brushes or fans and an accompanying flow, the fans soon disappearing and the glow becoming uniform and increasing in brightness. The positive glow generally begins at lower voltages for the corroded surfaces than for the polished surfaces.

The negative visual corona for the corroded surfaces is likewise similar to that for abrased surfaces at different pressures. Clear cut and steady beads are obtained at the lower pressures but are not so stable for the higher pressures. In general the negative starting voltage is lower than for polished surfaces.

(6) In order to show a few results photographically a wire having one-third of its length polished, one-third corroded, and one-third mechanically abrased was placed in a tube with a longitudinal slot, and photographs were taken when the corona was on the wire. Fig. 21 contains photographs of the negative wire, the left end being abrased, the center polished, and the right end chemically corroded.

These photographs show that the beads begin on the polished surface, that the corroded surface shows no glow, and that the abrased surface has only a slight brush discharge on it. The beads on the polished surface are very large, clear, steady, and evenly spaced. Fig. 21, *b* shows the effect of a slight increase in voltage where the glow now appears on the corroded surface and the beads begin to form on the abrased surface. Gradually increasing the voltage and the pressure as well causes the glow to become brighter on the polished surface and the beads to increase in number on the abrased and corroded surfaces. The beads on the abrased portion have a lateral movement, while those on the polished part are still very steady and clear.

With a still greater increase in pressure and voltage it is possible to reach a condition where the whole length of the wire is covered with clear, steady, and evenly spaced beads (Fig. 21, *c*). Here it seems that the surfaces all act very nearly the same in the formation and building of the corona discharge.

When the pressure is increased to 370 mm. and the voltage is sufficiently high to produce the discharge, the corona starts first on the abrased portion and only on this part can steady, clear beads be obtained (See Fig. 21, *e*). The beads on the corroded part are fairly well defined, but they are in an agitated state. Under these conditions it is found impossible to get steady beads on the polished part of the wire; instead of the clear beads there is a rather knobby glow on the wire, the condensations in which seem to be beads trying to form.

This reversal of the phenomena, the clear beads forming on the polished surface at low pressures and on the abrased surface at high pressures as shown in Fig. 21, actually occurred for steel wire. The corona starts first on the polished wire for low pressure and begins on the abrased or corroded wire at much lower potentials for high pressures.

An enameled german silver wire was fitted into the tube after half of its length had been freed from the enamel and polished. At low pressures for the positive wire the characteristic glow appeared on the polished end. The enameled end had several small starlike spots of light which were irregularly distributed and which appeared at points where the insulation had failed. Keeping the wire positive and increasing the voltage caused very bright "streamers" of purple light to shoot from a few of these small stars. At higher pressure and higher voltage these streamers increased greatly in number, the glow spreading out into a thin fan-shape. This fan slowly oscillated about the bright spot on the wire as a center. Between the fans a hazy fog-like glow was present. When an arc was placed in series with the wire and the tube, this fog disappeared and the fans became more sharply defined and steadier than they were.

For the wire negative (see Fig. 22, *e*) it was not possible under any conditions to get the characteristic negative beads nor could a glow be produced on the polished end. The only discharge present was on the enameled end and was similar in appearance to the small stars for the positive wire. For the negative wire, however, the stars were intensely bright and in slight movement. Fig.

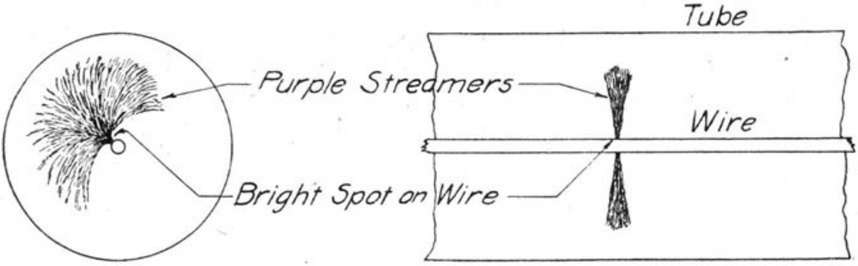


FIG. 23. STRUCTURE OF THE POSITIVE PURPLE FANS, UNDER CONDITIONS GIVEN IN FIG. 22.

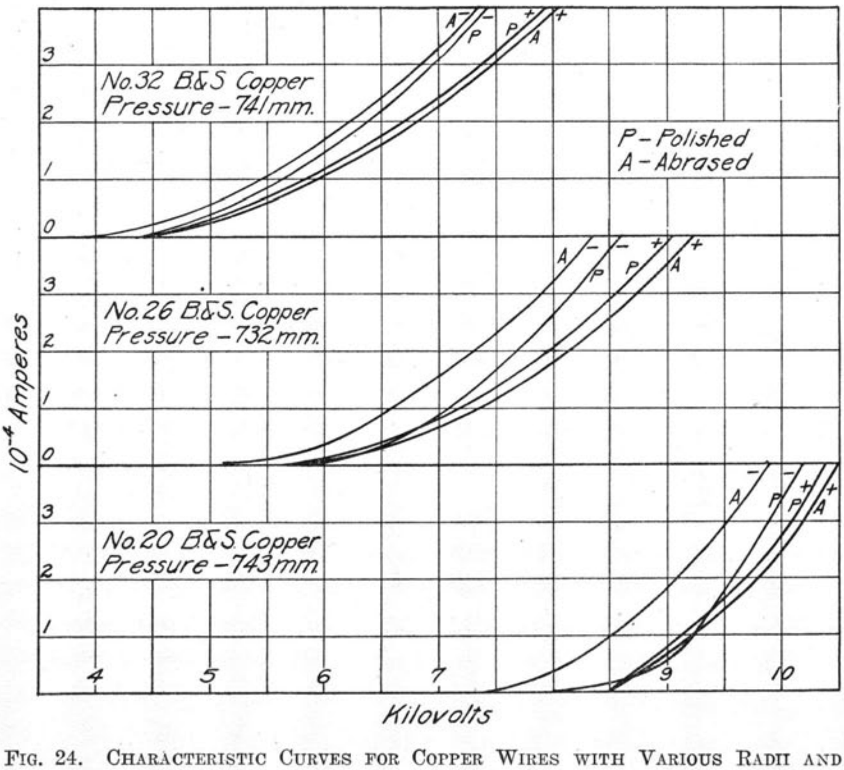


FIG. 24. CHARACTERISTIC CURVES FOR COPPER WIRES WITH VARIOUS RADII AND SURFACES

22 shows the appearance of the discharge from the enameled wire when it is both positive and negative. Fig. 23 gives details of the structure of the positive purple fans. For the enameled wire negative the starting potential was much lower than for the opposite polarity.

(7) The curves in Fig. 24 are taken for varying sizes and different surfaces of copper wire.

In *e*, Fig. 22, the surprising fact is shown that the negative discharge passes through the enameled part of the wire, while the free metal surface shows no trace of a glow. The curves show that the effect of abrasion in general lowers the starting point for copper wires at atmospheric pressure. The curves for the negative abrased wire are widely displaced from those of the polished wire; thus it is shown more current flows in the corona discharge for the same voltage for wire abrased than for the smooth wire. The curves showing the discharge for the positive abrased wire quickly cross those for the polished wire and then continue to rise slightly displaced, less current flowing for the same potential abrased than for polished. The abrased surface has, thus, the effect of restraining the flow of the positive current.

The effect of abrasion is much greater in the negative than in the positive current. The curves also show that this effect is greater for the larger wires, as might be expected. The higher starting potential for the larger wires is also evident.

The negative current builds up very slowly at first on the polished surface but finally reaches a point where it builds up much faster than the positive, and at this point the beads are formed. The starting voltage for the abrased surface negative is much lower than for polished surface negative. The characteristic curve of the abrased wire is a smooth rising one which eventually crosses the polished negative curve for large current values. This same phenomenon has been observed for different metals.

Fig. 25 gives the characteristic positive and negative curves for aluminum wires at about 50 mm., and shows the effect of the three surface conditions,—namely, polished, abrased, and corroded. The starting positive wire voltage for the smooth surface is slightly lower than that of the negative, but the curves cross low, the positive current building up slowly with increased potential while the negative curve is almost a straight line which rises very rapidly. The positive starting potential is higher for the abrased surface than for the polished, while that for the negative abrased surface is lower. The negative polished and abrased surface curves cross, but the positive do not. For the corroded surface the positive glow voltage is about the same as for the polished surface, the curve for the former condition becoming displaced shortly, less current flowing for the same voltage. The negative starting potential is very much lower in the latter case than that for the polished surface, but crosses at a low current value and rises to the right, less current flowing for the same potential.

Thus it is seen that the surface condition has a very marked

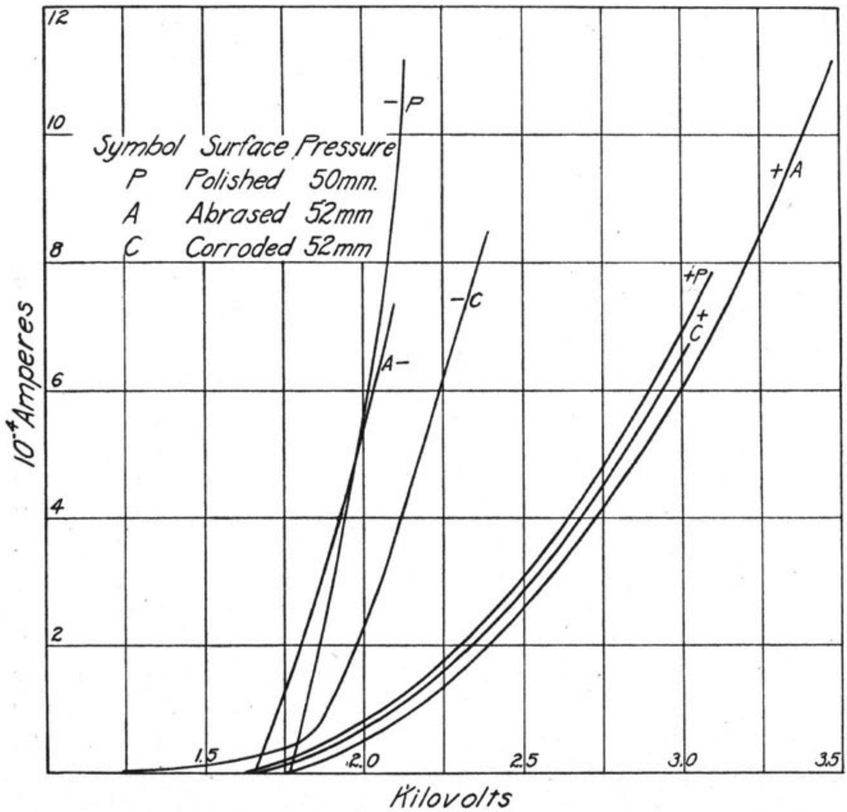


FIG. 25. CHARACTERISTIC CURVES FOR ALUMINUM WIRE OF 0.45 MM. DIAMETER WITH VARIOUS SURFACES

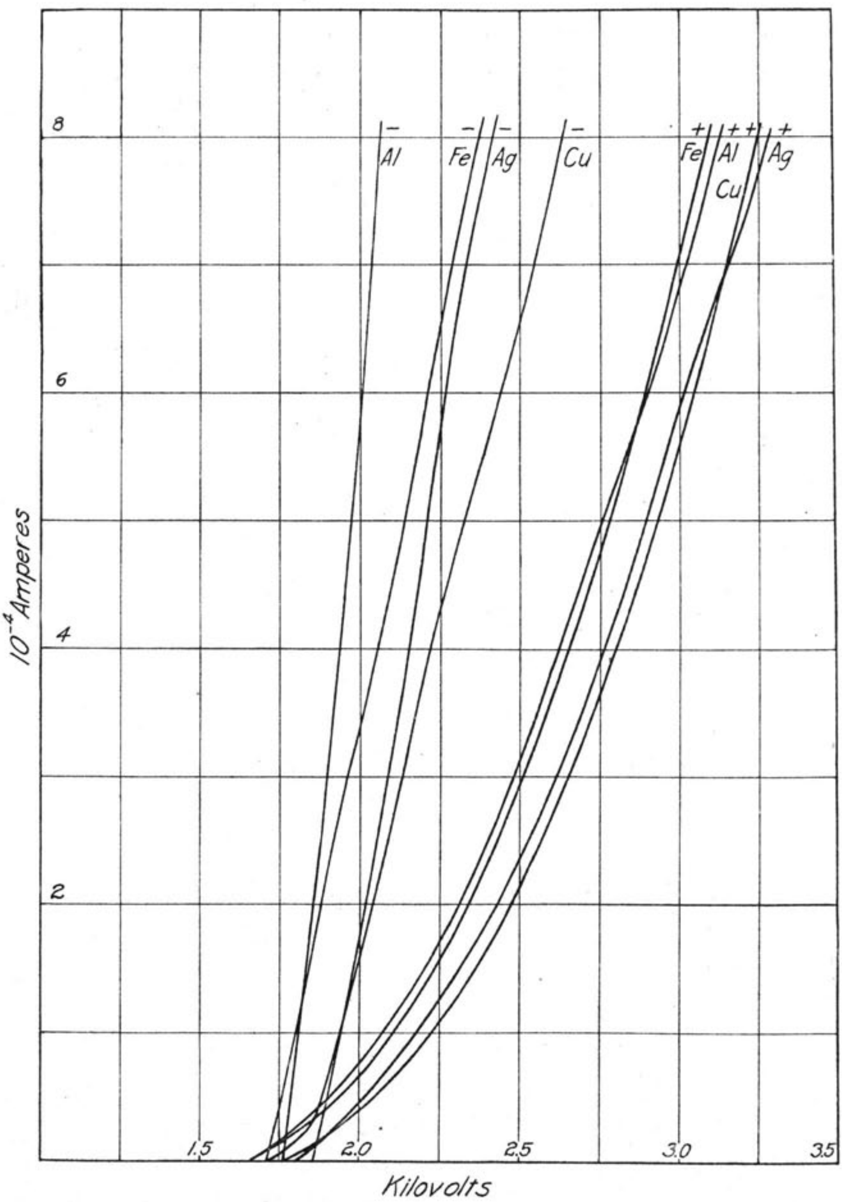


FIG. 26. A COMPARISON OF THE CHARACTERISTIC CURVES SERIES OF DIFFERENT METALS

effect on the starting point of the corona as well as on the characteristic curves. All the wires were about 0.41 mm. in diameter. In general the abrased surface has the effect of lowering the starting potential for negative wire and raising it for positive wire. The starting point for both positive and negative corona in the case of corroded wires is in general lower than that for the polished surfaces, but the corroded surface characteristics behave in rather an erratic manner, sometimes being displaced in one way and sometimes in the opposite.

Table 3 gives a comparison between the corroded and polished wire characteristics for both positive and negative surfaces at different pressures.

The curves in Fig. 26 show a comparison between the characteristics of different metals. Very marked differences are evident in the characteristic curves and show directly that the metal itself has a

TABLE 3

COMPARISON OF CORRODED WITH POLISHED WIRE CHARACTERISTICS

Wire	Press	Starting Pot.	Corroded Surface Characteristic
		COPPER	
−	50.2	Lower	Raised
+	50.4	"	"
−	250.0	"	Crosses high
+	250.8	"	Raised
		STEEL	
−	53.2	Higher (press. diff.)	Crosses high
+	52.4	Lower	" "
−	252.0	"	" low
+	252.4	"	Lowered
−	739.4	"	Crosses high
+	739.4	"	" low
		ALUMINUM	
−	51.9	Lower	Crosses low
+	51.9	"	" "
−	252.0	"	" midway
+	252.0	"	Raised
−	745.3	"	Crosses midway
+	745.4	"	Raised
		SILVER.	
−	52.5	Same	Lowered
+	52.5	Lower	"
−	252.2	Same	Crosses low
+	252.2	Lower	" midway
−	745.8	Higher	Lowered
+	746.1	"	"

part to play in the corona formation. The positive and negative characteristics, especially for aluminum, become widely separated for large currents. The curves for the other metals separate at different rates for increasing current values, but in such a manner that each metal behaves in its own characteristic way.

Slight differences in the starting points for the different metals were noticed; these differences, however, are of such a nature that they cannot be explained as being experimental errors. Steel and copper seem to have about the same starting point, while that for aluminum is a little higher and silver has a value still greater. The different metals not only affect the behavior of the characteristic curves but also the starting points of the corona glow.

The formation and number of the negative beads depend not only on the pressure and potential, but also on the surface condition and the material of the wire. The current per bead is larger for the abrased and corroded surfaces than for the polished surface, with the assumption that the whole current is to be carried by the beads. For an increase in pressure it is also seen that the current per bead is much less for the polished surface than for the others, but the beads are smaller in size. For the higher pressures it takes, however, a larger voltage to produce the same number of beads. For the lower pressures the beads have about the same degree of stability for all the different surfaces, while for higher pressures the beads are more stable on the abrased or corroded surfaces than on the polished, it being almost impossible to get definite beads on the polished wire for atmospheric pressures.

The number of beads increases rapidly with increasing voltage. Here again the effect of the materials is compared. For the production of the same number of beads it takes in general a greater voltage on the steel than on the copper and aluminum wires.

CHAPTER VI

Alternating Current Rectification

19. *Suggested by a Comparison of the Air and Hydrogen Characteristic Curves.*—Fig. 9 shows that the discharges through air and hydrogen were very similar in so far as the variation between critical voltage and radius and pressure are concerned. The curves in Fig. 27 show clearly the difference between the corona in air and in hydrogen. The two curves on the left side of the figure refer to

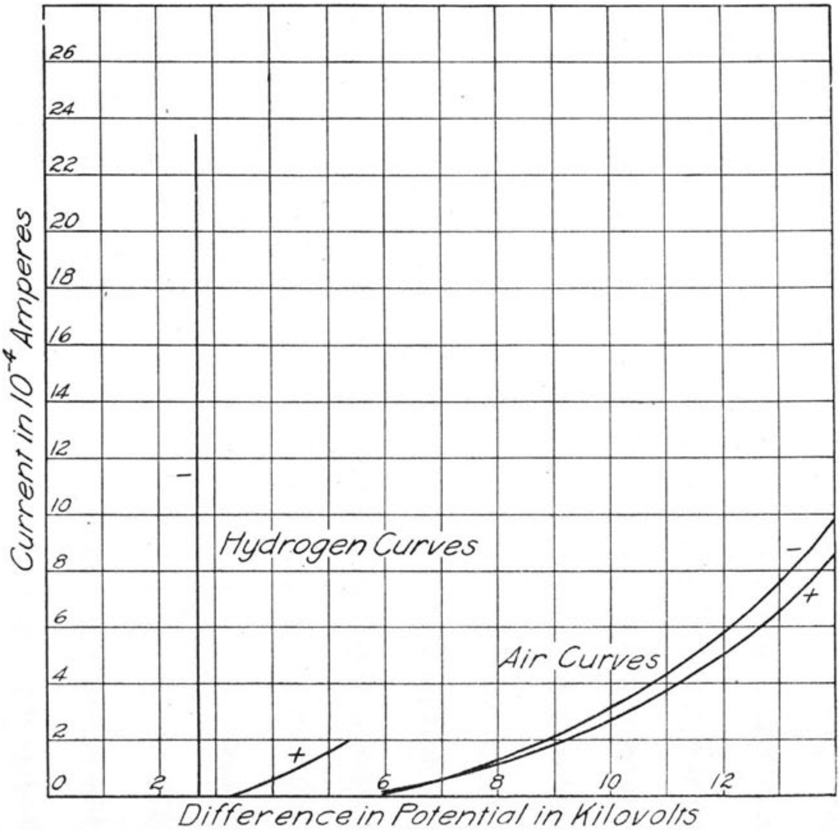


FIG. 27. COMPARISON OF CORONA IN AIR AND HYDROGEN UNDER SIMILAR CONDITIONS

hydrogen, while the curves on the right show results obtained with air. The data for these curves were obtained with wires of approximately the same diameter. These curves show two distinct differences between corona in air and in hydrogen.

In air the positive corona starts at a lower voltage than the negative, while the reverse is true when the dielectric is hydrogen. The other and more important difference is the entire dissimilarity of the positive and negative curves with hydrogen. This difference has not been found with air. A single glance at this curve shows that corona in hydrogen between a wire and a tube is an effective means of accomplishing rectification. This statement is true since large currents may be obtained from a negative wire with voltages which will give little or no current from a positive wire. This rectification may be accomplished with the wire cold and is not a case of rectification by means of a hot cathode. The principal of electron emission from a hot cathode might be used, however, in connection with the corona rectification.

20. *Description of Apparatus and Tests.*—To show that rectification was possible the corona tube was connected to an alternating source of voltage. A sensitive oscillograph element was connected directly in series with the corona tube and another element was connected across the primaries of the transformers. A diagram of the connections is shown in Fig. 28.

21. *Oscillograms and Their Interpretation.*—Fig 29 gives the current and voltage curves when an alternating voltage is impressed across a corona tube. The curve having both positive and negative lobes represents the voltage. The non-symmetrical character of this curve is due to the drop in the resistance in series with the primaries of the transformers. The curve lying mainly below the axis represents the current flowing between the wire and tube. The part of this curve slightly above and slightly below the axis is of the same shape and order of magnitude as the charging current of the condenser formed by the wire and cylinder. This fact was determined by an oscillogram taken at a voltage slightly less than that necessary to form corona.

The voltage at which negative corona starts, as shown in this oscillogram, is approximately twice the voltages across the tube at the instant that the discharge ceases.

The rectification with corona in hydrogen is practically perfect as is shown by the oscillograms in Figs. 29 and 30.

In an investigation, interrupted by the World War, J. W. Davis has shown that alternating currents may be perfectly rectified up to 42,000 volts made effective by means of the corona in hydrogen. The rectification is, however, not of very high efficiency as a large part of the energy is transformed into heat in the corona tube. For a given gas pressure the maximum voltage which may be rectified or, in other words, the voltage at which the arc sets in between the coaxial cylinders is nearly directly proportional to the radius of the outer cylinder, when the radius of the inner cylinder is small compared with that of the outer cylinder. In order to improve the efficiency of the rectification the central wire was heated. An incandescent wire gave rise to the corona discharge at voltages much lower than those necessary to start a discharge from a cold wire. The initial state of ionization around the wire has a very marked effect on the critical corona voltage. When the central wire is heated to incandescence and then the high voltage applied, the temperature of the wire will change very much, especially towards the ends where the wire appears almost dark, while in the middle the temperature may fall to that of dull red heat. This fall of temperature is undoubtedly due to the wind set up in the corona. Fig. 31, from Davis' unpublished paper, will show a rectification at 42,000 volts.

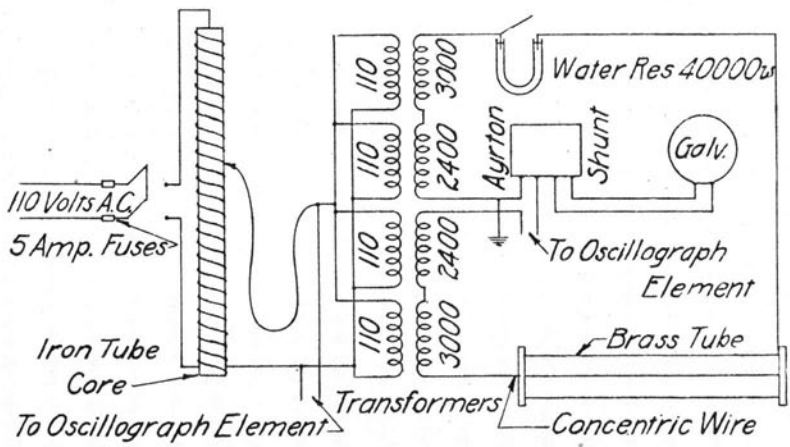


FIG. 28. DIAGRAM OF CONNECTIONS FOR ALTERNATING CURRENT RECTIFICATION IN HYDROGEN

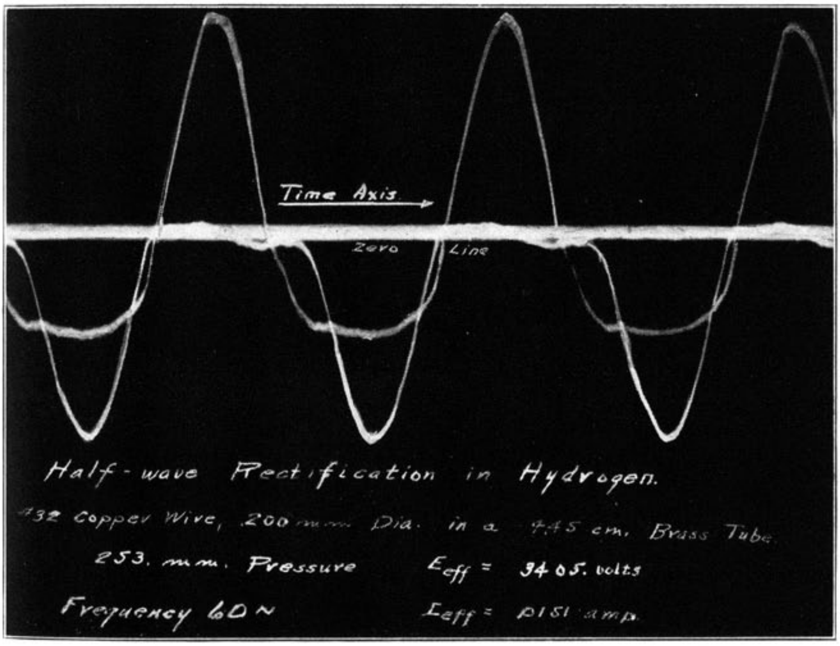


FIG. 29. OSCILLOGRAM

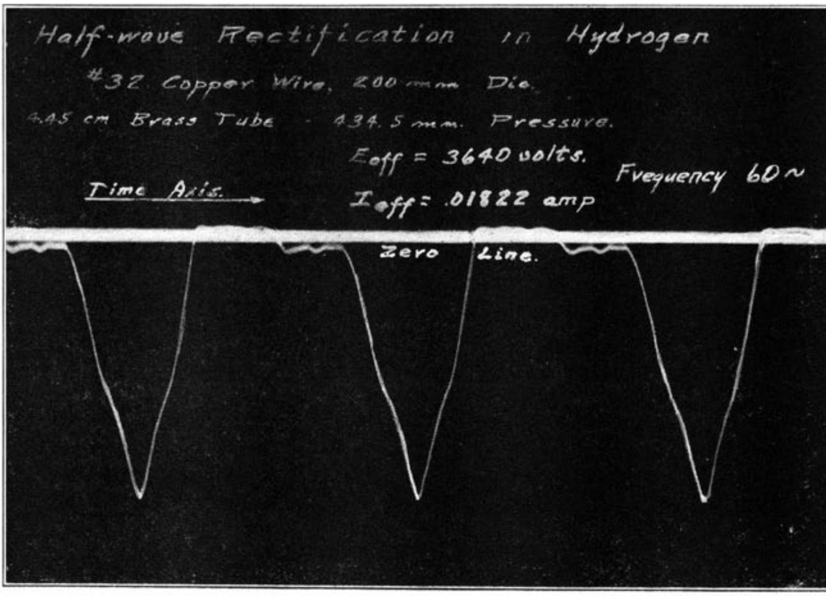


FIG. 30. OSCILLOGRAM

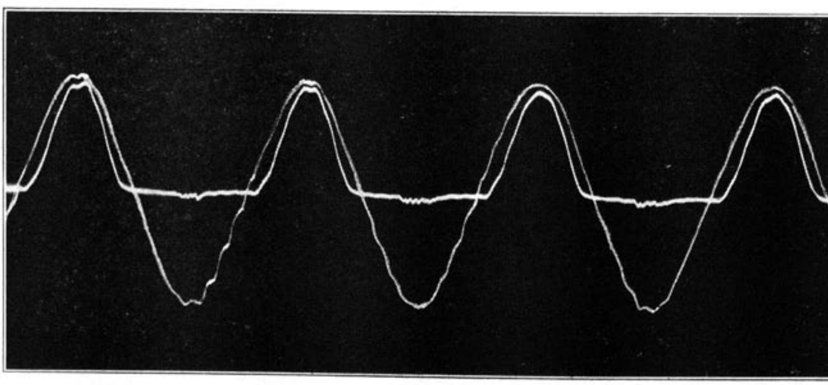


FIG. 31. OSCILLOGRAM SHOWING RECTIFICATION AT 42,000 VOLTS

CHAPTER VII

Distribution of Potential in the Corona Tube

In order to develop any complete corona theory a knowledge of the distribution of the potential between the electrodes is necessary. The distribution of potential between the wire and the coaxial cylinder was investigated in the following manner.

22. *Method and Apparatus.*—A hole was drilled in the side of a cylinder, and an insulated wire terminating in a bare spherical tip was arranged so that it could be moved radially between the wire and the tube. A micrometer microscope directed on a fixed point of the movable wire served to determine the relative position of the point. An electrostatic voltmeter of small capacity was connected in series with the exploring point and the tube.

When the point was moved to any position in the radial field, the voltmeter quickly showed a constant deflection and indicated that the potential of the point was in equilibrium with that of the field at that particular place. By moving the exploring point from the tube

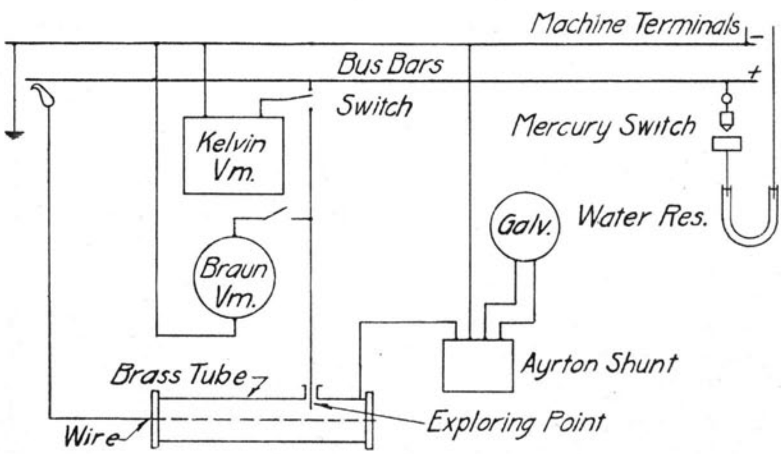


Fig. 32. Diagram of Connections of Apparatus for Determining the Distribution of Potential in the Corona Tube

to the wire and observing the voltmeter readings at certain intervals, one obtained a comparatively accurate estimate of the intensity of the field. The apparatus and connections are shown in Fig. 32. The tube used in this investigation was 35.5 cm. long and 7 cm. in diameter. The wire was copper, well polished, and stretched tightly. In all, four wires were used, No. 40, No. 32, No. 28, No. 20, B. & S. gage. Since it was necessary to work at pressures lower than atmospheric,

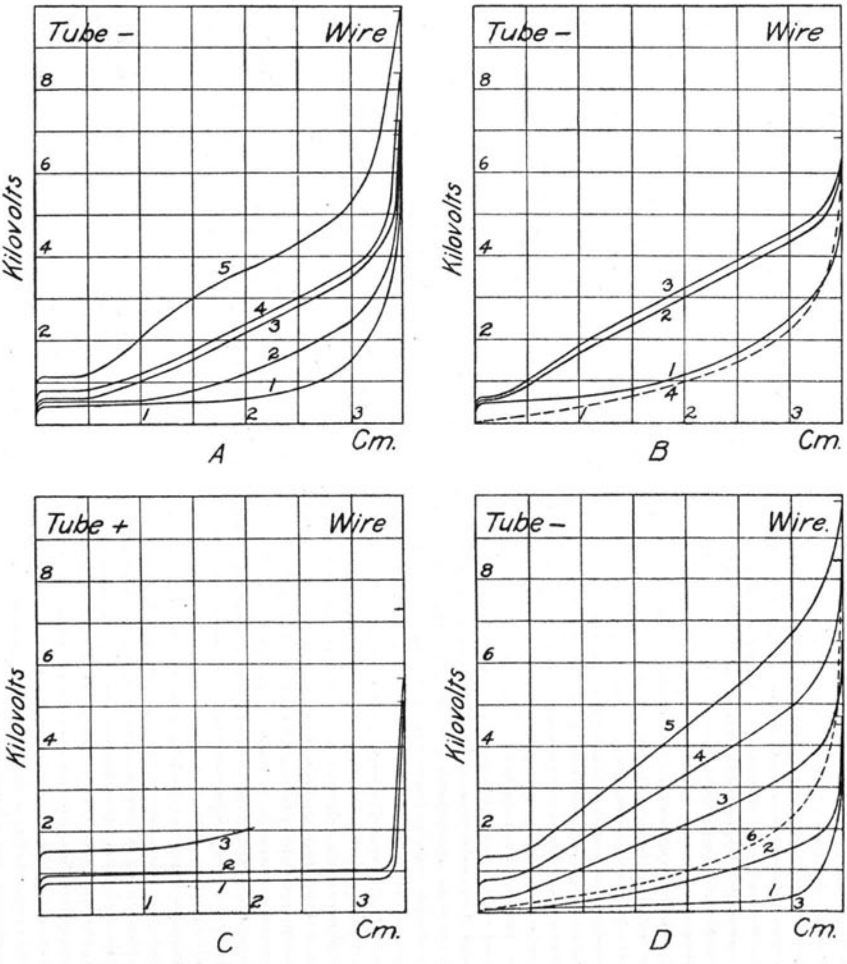


Fig. 33. Representative Curves Showing Distribution of Potential in the Corona Tube

a glass tube was sealed over the exploring rod and arranged with ground points and springs so that the point might move at will without destroying the constant pressure.

23. *Results Obtained.*—By this method, curves were taken for various pressures and voltages after the appearance of the corona. Representative curves are shown in Fig. 33, and the conditions under which each curve was taken are given in Table 4.

For the smaller wires it was found difficult to obtain data for curves when the wire was negative, because the voltmeter would not come to rest and give a definite reading. For a No. 32 wire, when the wire was negative, two curves shown in Fig. 33*C* were taken before the corona appeared, also a portion of a curve for a voltage at which there was a distinct series of beads along the wire.

Curves were also obtained for No. 28 and No. 20 wire when the wires were negative, the same general characteristics being exhibited in each.

Curve 4, Fig. 33*B*, shows the distribution of potential as given by electrostatic theory. This theory assumed, of course, that there are no charges in motion in the gas: that is, that there is no current. It is seen that the actual distribution is very different from what it

TABLE 4

TABLE OF DATA FOR CURVES

Figure	Curve	Wire B. & S. Gage	Voltage	*I* Amperes	*P* Mm. of Hg.	Temp. C.	Remarks
33*A*	1	32	6 510	$4.17.10^{-8}$	747	25°	No glow
	2	32	6 825	$1.91.10^{-6}$	747	26°	Distinct glow
	3	32	7 425	$1.91.10^{-5}$	747	26°	Good glow
	4	32	8 400	$5.94.10^{-5}$	747	26°	Good glow
	5	32	9 900	$9.54.10^{-5}$	747	26°	Bright glow
33*B*	1	32	6 825	$1.91.10^{-6}$	747	26°	Distinct glow
	2	32	6 825	$2.03.10^{-4}$	241	24°	Bright glow
	3	32	6 825	$3.46.10^{-4}$	885	24°	Brilliant glow
	4	32	6 825	Electrostatic	curve		
33*C*	1	32	5 050	$1.79.10^{-8}$	744	26°	No glow
	2	32	5 650	$2.39.10^{-6}$	744	26°	A few dull beads
	3	32	7 250	$3.10.10^{-5}$	744	26°	Beads 1 cm. apart
33*D*	1	40	4 520	$4.77.10^{-8}$	740	22°	No glow
	2	40	4 700	$1.19.10^{-6}$	740	22°	Distinct glow
	3	40	6 500	$2.26.10^{-5}$	740	22°	Good glow
	4	40	8 400	$8.29.10^{-5}$	740	22°	Good glow
	5	40	9 900	$1.67.10^{-4}$	740	22°	Brilliant glow
	6	40	8 400	Electrostatic	curve		

would be if there were no current. The detailed discussion of the curves will be considered under the two polarities.

In general for the positive wire the space between the anode and the cathode may be broken up into four regions:

> (1) A region immediately surrounding the wire, which is characterized by a very large potential gradient. This gradient may be due to the excess of the number of ions or electrons approaching the electrode over the number of those leaving, since the former number includes ions generated at all parts of the field; whereas the latter contains only ions that are generated in the narrow layer close to the wire. It is, therefore, evident that the charges on the excess of negative ions near the wire disturb the electric field so that the potential difference per centimeter, or the gradient, is large near the surface of the wire.
>
> (2) A region of approximately constant force extending from the "surface layer" region adjacent to the wire to a point which varies with the pressure, current, and voltage. At the higher voltages, the actual potential at a given point in this region is greater than the theoretical electrostatic potential, and the tangent to the curve may be either greater or less.
>
> (3) A region of little or no force near the tube, but not touching it.
>
> (4) A region adjacent to the tube, where positive charges accumulate and form an abrupt cathode drop of potential.

When the wire is negative and corona appears, a potential curve is obtained which differs somewhat from the positive curves. Large cathode and anode drops appear, and the intervening space has a very small field. Reasoning similar to that which explains the shape of the curves when the wire is positive explains the negative curves.

So in general, the anode and cathode drops of potential are predominant in both types of curves. There are several reasons for this: namely,

(1) Polarization potential between a metal and a gas.
(2) Accumulation of ions.
(3) Reflection of ions.
(4) Different velocities of positive and negative ions.
(5) A non-uniform field.

For a system where the potential at a point is due to moving charges as well as static charges, there is Poisson's equation expressing the density in terms of the potential

$$\triangle^2 V = -4\pi\rho,$$

or, expressed in cylindrical coördinates,

$$\frac{\delta^2 V}{\delta r^2} + \frac{1}{r}\frac{\delta V}{\delta r} + \frac{1}{r^2}\frac{\delta^2 V}{\delta \phi^2} + \frac{\delta^2 V}{\delta z^2} = -4\pi\rho$$

For this particular case, the derivatives in z and ϕ are zero; so rewriting this equation and using total derivatives gives

$$\frac{d^2 V}{dr^2} + \frac{1}{r}\frac{dV}{dr} = -4\pi\rho = \frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right). \quad . \quad . \quad . \quad (8)$$

Since the density is an undetermined function of the radius, the equation cannot be integrated directly. If, however, the potential is plotted against the distance from the axis, a graphical method will aid in the determination of the density; that is, if the first derivative

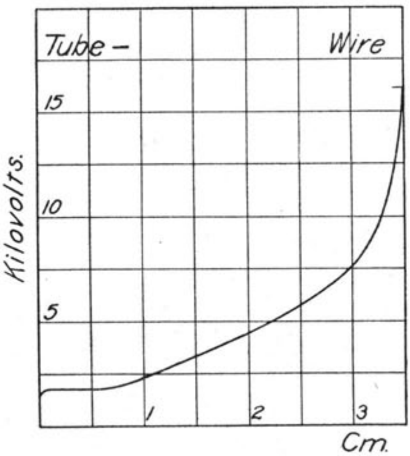


Fig. 34. Experimental Curve of Distribution of Potential in the Corona Tube

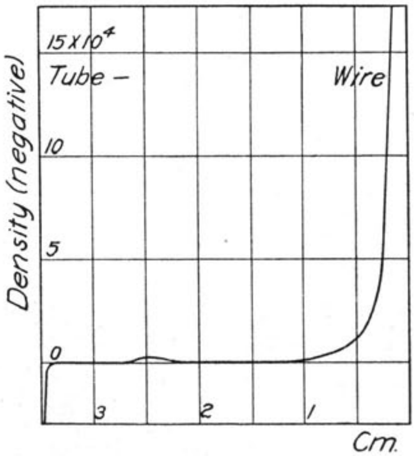


Fig. 35. Computed Curve of the Volume Density of Electrification in the Space between the Wire and the Tube

of the potential is determined from the curve for a series of values of r, these new values may be plotted against the radius again. Repeating this process with the derived curve gives a relation between the second space derivative and the radius. From these two derived curves, then, the density may be computed according to equation (8).

Fig. 34 is a curve of the same type as curve 4 in Fig. 33*A*, and Fig. 35 shows the density as computed for the different values of r.

The density curve shows that which was deduced intuitively in regard to the changes necessary to produce the observed distortion of the field. The large resultant negative charge near the positive wire and the positive charge near the negative tube should be expected. A peculiar maximum appears about 2.7 cm. from the wire.

Sources of error are found in the potential assumed by a sphere in an ionized gas. It is difficult to draw conclusions concerning the absolute potential of a sphere in a conducting gas, since it is very likely that the potential at an undisturbed point in a gas is not the same as the potential assumed by a sphere when its center is at this point.

In a sphere near the positive electrode, the potential being initially the same as that of the gas, two streams of ions move in opposite directions past the side of the sphere, one containing a large number of negative ions and the other a smaller number of positive ions. The sphere intercepts more negative ions than positive so that its potential falls below that of the surrounding gas. The charge thus acquired by the sphere increases until the effect which it produces in attracting positive and repelling negative ions causes them to come in contact with the sphere in equal numbers. The final value of the potential assumed by the sphere is too high by an amount which depends upon the relative velocities of the positive and negative ions.

Conversely, when the exploring sphere is close to the negative electrode, there is a greater number of positive than negative ions intercepted so that the potential of the sphere rises above the potential of the undisturbed gas, until finally an equilibrium is reached. The number of positive charges acquired by the sphere is equal to the number of negative charges; thus the potential assumed by the sphere is greater than that of the undisturbed gas. If, however, the velocity of the positive ions is approximately equal to that of the negative ions, the exploring point should attain very nearly the same potential as that of the surrounding gas. For the pressures used in this series of experiments, the velocities of the ions are nearly the same. The error introduced could not, therefore, have been very great.

A slight error might be introduced if there were an appreciable voltmeter leakage between the point and the power line. The shape of the point also affects that of the potential curve to a small degree. The voltmeters used were practically free from leakage, and the work was done during cold, dry weather; so the error introduced from this cause is negligible.

CHAPTER VIII

The Pressure Increase in the Corona

Dr. S. P. Farwell was the first investigator to discover that at the instant the corona appeared on the wire the gas pressure in the corona tube increased. The increase appears very suddenly and also disappears very rapidly. For these reasons all the experimenters working in this laboratory have maintained that the pressure increase could not be due to heat. It has been suggested that it might possibly be due to ionization. This assumption is a possible consequence of the present theories of the corona, which assume it to be an ionization phenomenon. These theories assume that the high potential differences cause the few ions which are always present in a gas to move with a velocity sufficiently great to break the molecules with which they collide into two parts, one bearing a positive and one a negative charge. All these charged particles then move, because of the influence of the field, toward one or the other of the terminals. The presence of these ions thus explains the conductivity of the gas, and the acceleration of the ions explains the light effect. If the corona is an ionization phenomenon one would expect, provided the corona apparatus were enclosed, at the instant the corona appeared; i. e., at the instant the molecules were broken into ions, that the pressure in the apparatus would increase, because according to kinetic theory the greater the number of particles in a given volume the greater the pressure. Under certain circumstances the pressure increase can amount to as much as 3 cm. of mercury.

Professor Kunz (9), by theoretical considerations, has shown that this increase in pressure should be exactly proportional to the corona current.

Other investigators (10) have contended that the pressure increase could be completely accounted for as the result of Joule's heat and that the assumption that it is due to ionization is untenable. To support this contention Arnold performed experiments "by electrically heating the central wire in apparatus similar to Farwell's" and observed the pressure increase. With such an apparatus Arnold attempted to show: (1) that an increase in pressure due to heat ap-

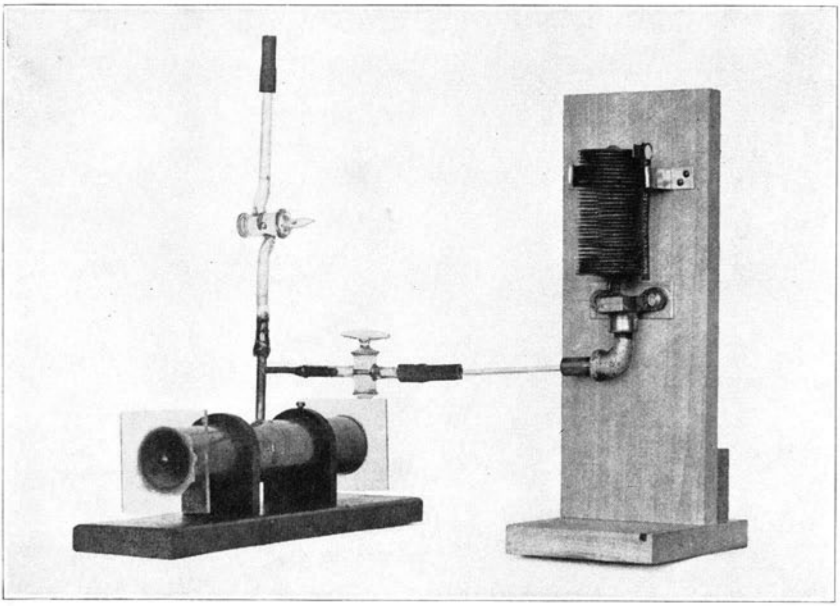


FIG. 36. APPARATUS FOR STUDY OF THE PRESSURE INCREASE IN THE CORONA TUBE

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pears suddenly, and (2) that for a given power consumed in the tube the increase in pressure due to heat is of nearly "the same magnitude as those observed" in the corona.

In order to show clearly that the pressure increase is not due to heat a series of comparative experiments was performed with the pressure increase, caused (1) by producing the corona glow on the wire, and (2) by heating the central wire. The pressure increase observed in the first set of experiments will be referred to as *caused by corona* and in the second set as *caused by heat*. A few computations have also been made which strengthen the results of these experiments.

Since the conception of ionization is so intimately associated with the idea of increase in pressure, it seemed important to determine the laws relating to this sudden increase in pressure to the corona current.

24. *Apparatus.*—To the corona tube was soldered a small T tube, one side of which was joined to the vacuum pump and the other side was connected to a Bristol aneroid pressure gage (see Fig. 36).

The increase in pressure was measured by this Bristol gage. Any increase in pressure caused it to bend slightly and to rotate the mirror. When the deflection of a beam of light was seen over a scale,

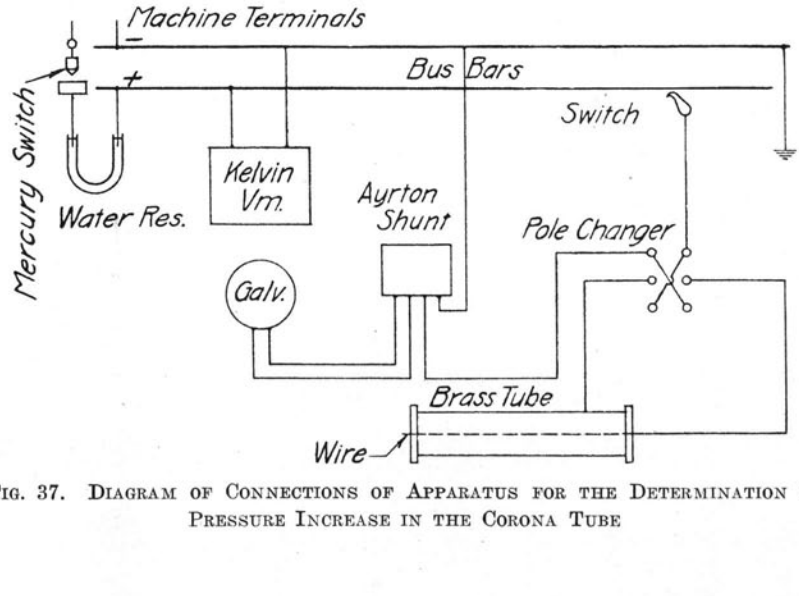

FIG. 37. DIAGRAM OF CONNECTIONS OF APPARATUS FOR THE DETERMINATION OF PRESSURE INCREASE IN THE CORONA TUBE

which had previously been calibrated by reading simultaneously the deflected beam and a water manometer connected directly to the gage, the increase in pressure in centimeters of water could be determined. The advantage of such a pressure measuring instrument in this experiment is its very quick action. The instant the pressure increases the gage jumps to its new position and a reading may be taken in a very few seconds. It was necessary to read this pressure increase quickly, because if much time was required the heating effect of the current would increase the pressure.

The current was measured by a Type *H* d'Arsonval galvanometer. The apparatus was connected as is shown in Fig. 37.

25. *Experimental Results.*—The results obtained from pressure increase in the corona were as follows:

(1) One who sees this pressure increase as recorded by a quick-acting pressure meter thinks it is not a heat effect, because of the rapidity with which it appears and disappears. Arnold showed that the pressure increase occurred very rapidly when caused by heat. The following curves show the difference in the rapidity in appear-

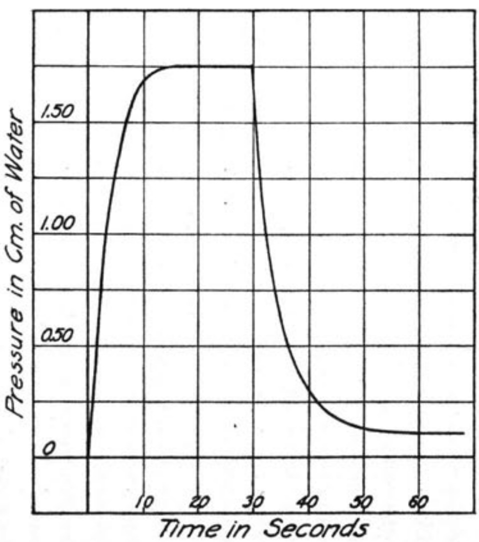

FIG. 38. PRESSURE INCREASE DUE TO HEAT

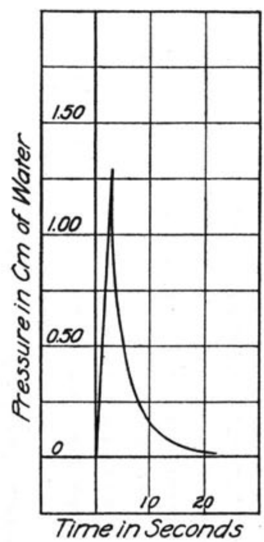

FIG. 39. PRESSURE INCREASE DUE TO CORONA

ance and disappearance of the pressure increase caused by heat and that caused by corona. It will be noticed in Fig. 38, where the pressure increase was caused by heating the central wire, that fifteen seconds were required for the pressure to come to its maximum value, and that from the time the current was broken twenty-five seconds were required for the pressure to return to practically its original value. In Fig. 39, however, where the pressure increase was caused by corona, only three seconds were required for the maximum pressure to be attained and the pressure came to practically its original value in eighteen seconds. In this last case from the appearance of the phenomenon, it seems, if the aneroid pressure meter had less inertia, that the pressure increase could be determined in less than three seconds. These curves show that the pressure increase appears five times as rapidly when caused by corona as when caused by heat and disappears also more rapidly.

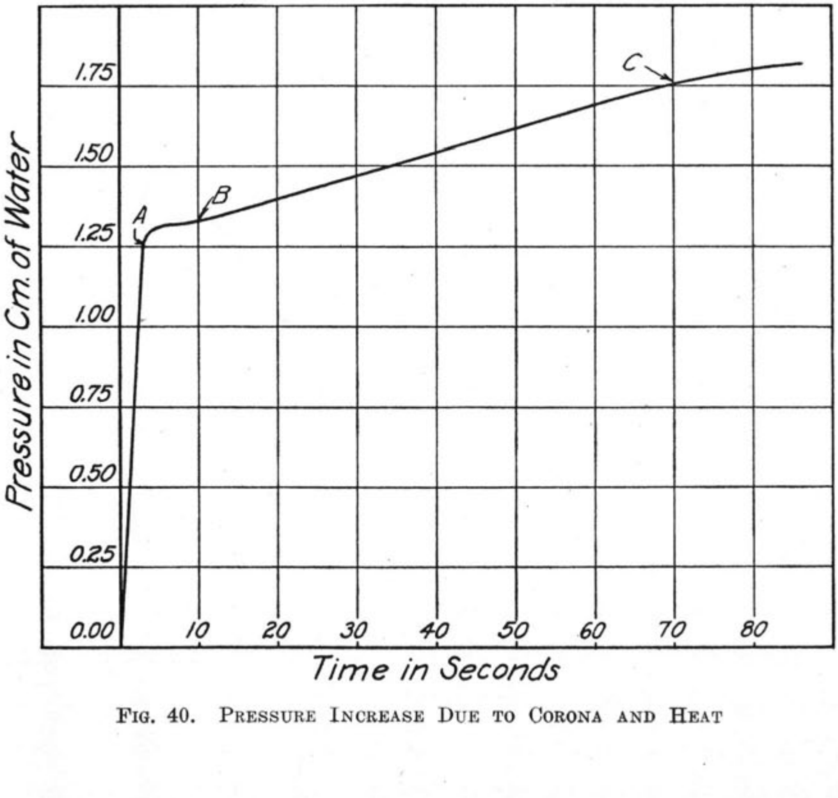

FIG. 40. PRESSURE INCREASE DUE TO CORONA AND HEAT

(2) In the pressure increase due to corona, a short time interval of five to seven seconds occurs after the sudden increase of pressure, before the heat effect in the corona begins to be noticed. This fact is shown in Fig. 40 by an abrupt bend, *a*, in the curve where the pressure increase is plotted against time. No such bend occurs where the pressure increase is caused by heat alone, as is shown in Fig. 38. In all the subsequent work the pressure increase measurements were always taken at a time corresponding to the point, *a;* by this means the heat effect is practically eliminated.

(3) The heat which is produced in the corona discharge, shown by the gradual pressure increase from *b* to *c*, Fig. 40, is distributed throughout the whole volume of enclosed air; consequently, when the circuit is broken, this heat does not radiate rapidly because the air is a poor conductor. This fact is shown very clearly in Fig. 41. The curve seems to show that the pressure increase due to heat in the corona is represented by the difference of ordinates of *c* and *b*, (Fig. 41). As soon as the circuit is broken at *c*, the increase in pressure due to corona at once disappears, but the increase in pressure due to heat in the corona discharge remains as is shown by the dif-

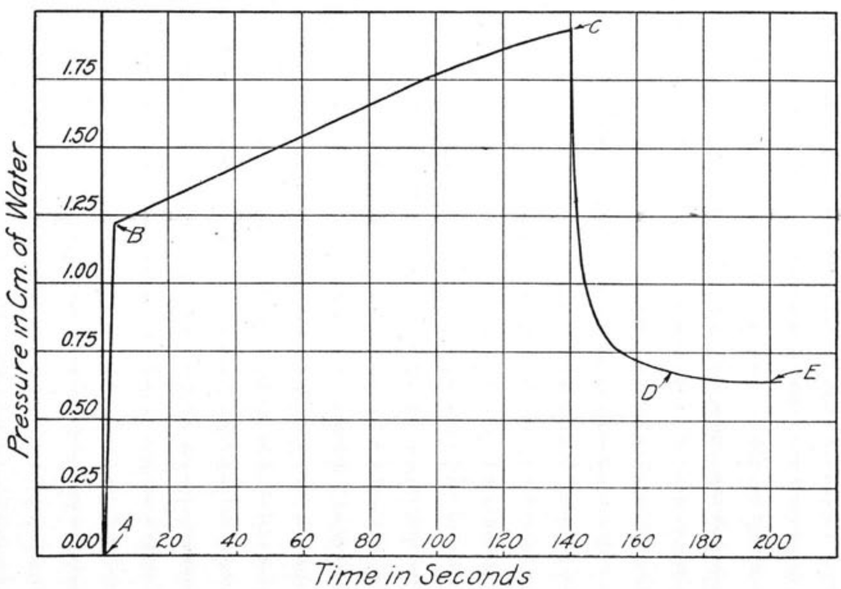

FIG. 41. PRESSURE INCREASE DUE TO CORONA AND HEAT

ference between ordinates d and a. This difference is always very nearly equal to the difference of ordinates of c and b. This heat energy produced by the corona current, since it is distributed through the gas, radiates very slowly, as is shown by the gradual descent of the curve from d to e. No such effect is observed when the increase of pressure is due entirely to heat, as is shown in Fig. 38. This curve shows that twenty-five seconds after the corona is removed from the wire the increase in pressure due to the corona has disappeared, but practically all the pressure increase due to heat in the corona (ordinate c minus ordinate b approximately equals ordinate d minus ordinate a) still remains and radiates very slowly.

(4) If the increase in pressure is due to heat, the same increase in pressure should result when the same power is consumed: (a) with a corona current through the gas and (b) with a heating current through the wire. Figs. 42 and 43 show that this is not the case. The powers consumed in the two cases are not exactly the same, but one can see that were they the same, the increase in pressure due to corona would be approximately half the increase in pressure due to heat. The power in the corona was obtained by multiplying the potential difference between the wire and the tube by the corona current, and in the heated wire the power was obtained by multiplying the current

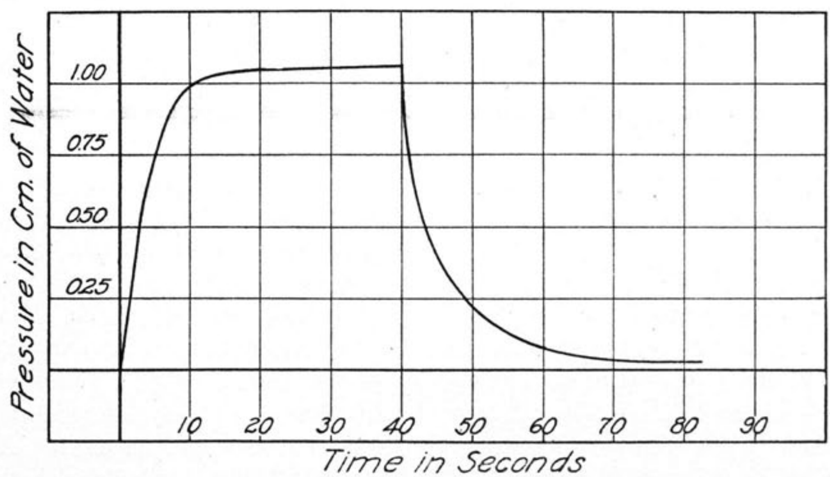

Fig. 42. Pressure Increase Due to Heat. Watts Consumed 0.238

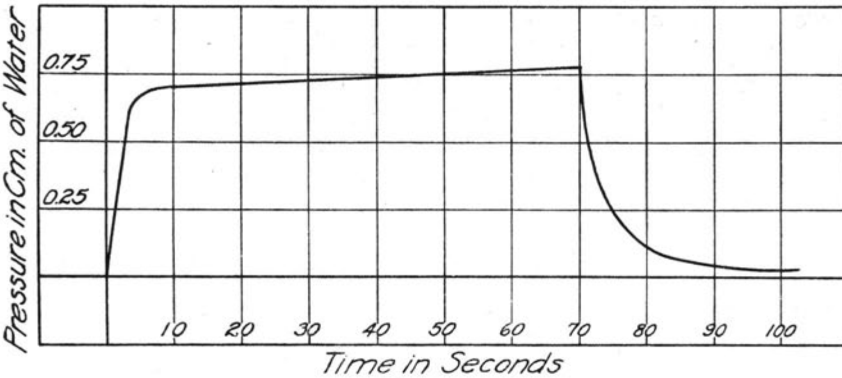

FIG. 43. PRESSURE INCREASE DUE TO CORONA. WATTS CONSUMED 0.266

through the wire by the potential difference across that portion of the wire which was in the tube.

(5) If the increase in pressure in the corona discharge is due to heat, the temperature of the air in the corona tube must increase. This condition may or may not be that of the luminous layer near the wire, but the temperature of the gas in the tube at a point four millimeters from the wire actually decreases. This decrease was determined by inserting a sensitive thermocouple made of very fine Copper-Advance wire into the corona tube. The temperature decreased only at the instant the corona appeared. In a short time after the heat due to the corona began to appear (corresponding to the slope *b* to *c*, Figs. 40 and 41) the temperature of the gas in the tube began to increase. This cooling effect is shown in Fig. 44. From a comparison of Fig. 44 with Fig. 40 it is seen that the increase in pressure which was measured at *a* was observed while there was an actual cooling in the corona tube. This cooling should be expected when air or oxygen is in the tube, for under these conditions ozone is formed. Since the formation of ozone from oxygen is always accompanied by an absorption of heat, the temperature of the air or oxygen would tend to lower. J. W. Davis, working on corona about hot wires in hydrogen, discovered that the appearance of the corona about a tungsten wire at white heat causes it to cool to dull red. This change tends to show that even in the corona glow itself there is a cooling effect. A possible explanation of the cooling effect might be given by assuming an electrical wind action around the conductor.

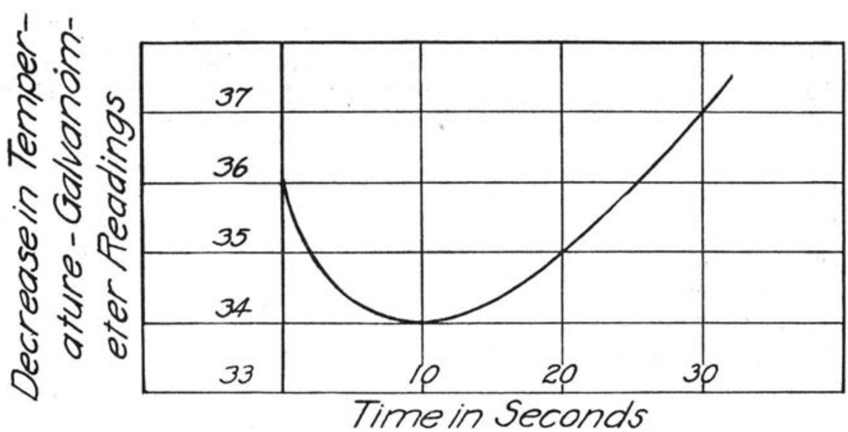

FIG. 44. COOLING EFFECT IN CORONA

(6) If the increase in pressure in the corona is due to heat, one should expect it to be the same with the wire either positive or negative. It will be mentioned hereinafter that it is impossible to obtain measurements when the wire is negative because of the presence of beads. The negative corona is entirely different from the positive corona.

(7) The following consideration will show, moreover, that the increase in pressure cannot be due to heat. The heat produced by the corona current will be given by the equation $H = 0.238\, eit$, and if the observed pressure increase is due to heat, the increase in pressure

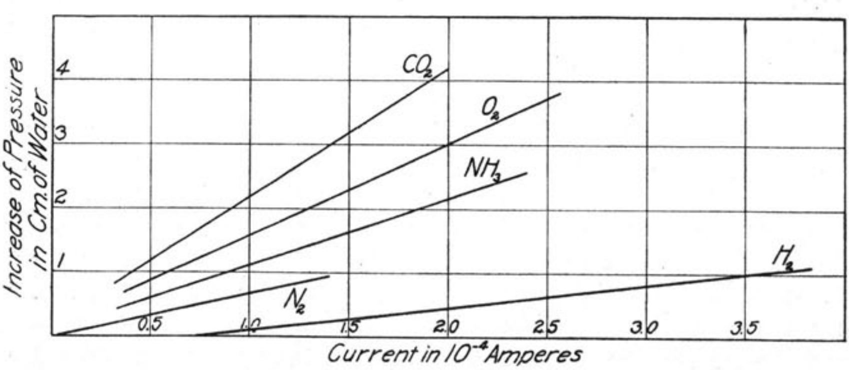

FIG. 45. RELATION BETWEEN IONIZATION PRESSURE AND CORONA CURRENT FOR DIFFERENT GASES

$\triangle p$ will be proportional to the heat. The equation may then be written $\triangle p = k\ eit$. The only way for $\triangle p$ to vary directly as i, the corona current, as shown by curves in the next paragraph, is for e to be independent of i. Data shows that this is not the case.

(8) To determine the laws relating this ionization pressure to the corona current, experiments were made when the wire was positive and the coaxial cylinder grounded with dry air, hydrogen, nitrogen, carbon dioxide, oxygen, and ammonia as the gases in the tubes. Considerable care was taken to see that these gases were absolutely pure. They were all dried carefully before they were used. Fig. 45 shows all the curves plotted to the same scale. With this scale the hydrogen curve should be continued until its ordinate is equal to that of the carbon dioxide curve.

The fact that the points all lie accurately on a straight line shows conclusively that the experiment verifies the prediction made by Dr. Kunz's theory. The law can then be stated that in the gases studied with the wire positive *the ionization pressure is exactly proportional to the corona current.*

In oxygen a considerable amount of ozone was formed because of the corona discharge. Evidently the curve as shown is a resultant of two effects: (1) A chemical change, due to the formation of ozone, which would tend to cause a decrease in pressure. (2) The increase in pressure due to the ionization of the oxygen. Since the ionization curve is a straight line, as is shown by the gases in which probably there is no chemical action, and since this resultant curve of oxygen is a straight line, the following law can be stated:

Whenever chemical change occurs because of the corona the chemical change is proportional to the current.

With the wire negative beads always appear, and since the pressure increase varies with the arrangement of the beads which are not stable, it is impossible to verify accurately the relationship. When an ordinary open manometer which is slow in its action was used instead of the quick acting gage, it was discovered that the same relationship as stated is very nearly true for the negative as well as for the positive wire.

The increase in pressure in nitrogen, showing ionization, is one of the exceptions where nitrogen is largely ionized at low temperatures and thus probably chemically active. How nitrogen, carbon dioxide, and ammonia are ionized are questions which require further study.

The arrangement of the apparatus could be used as a high potential voltmeter by simply calibrating the increase in pressure against volts, as determined by a disc electrometer.

26. *Results from Theoretical Considerations.*—If the increase in pressure is due to heat, it is possible to compute the magnitude of the pressure increase when one knows the watts of electrical energy consumed in the tube. The trial represented in Fig. 43 gives these data. The observed pressure increase was measured in three seconds so that the total number of joules of work consumed by the tube in that time was $3 \times 0.266 = 0.798$ joules. This amount corresponds to 0.1909 calories. Knowing the volume of the tube, the temperature and pressure of the air in it, one can readily compute the mass of the air in the tube. With the quantity of heat and mass of air mentioned previously, together with the specific heat of the air at constant volume, the temperature rise of the air can be computed, if the electrical energy is assumed to be converted into heat. This temperature rise is 2.44 degrees centigrade, which at constant volume corresponds to a pressure increase of nearly nine centimeters of water, while the observed pressure increase in this particular trial amounts to nearly seven-tenths centimeters of water. In this computation radiation and conduction losses have been neglected, because they would be very small from a body 2.44 degrees centigrade above room temperature. This computation shows that the observed results lie in a different order of magnitude from that expected if Arnold's theory were true.

Arnold states, if "we compute the corona currents that would result from the presence of enough ionized particles to produce the observed pressure changes, the currents calculated are many thousand times greater than those actually obtained." Such a statement is true only when the ionized particles are produced in a uniform or practically uniform electric field. This is not the case in the corona tube, as is shown in Chapter VII.

From these data it is seen that the potential gradient near the wire is very high, of the order of 30,000 volts per centimeter. This is the arcing gradient, in which probably every molecule is ionized. Then for a long space between the wire and the tube there is a very small gradient. With this condition of the field, every molecule may

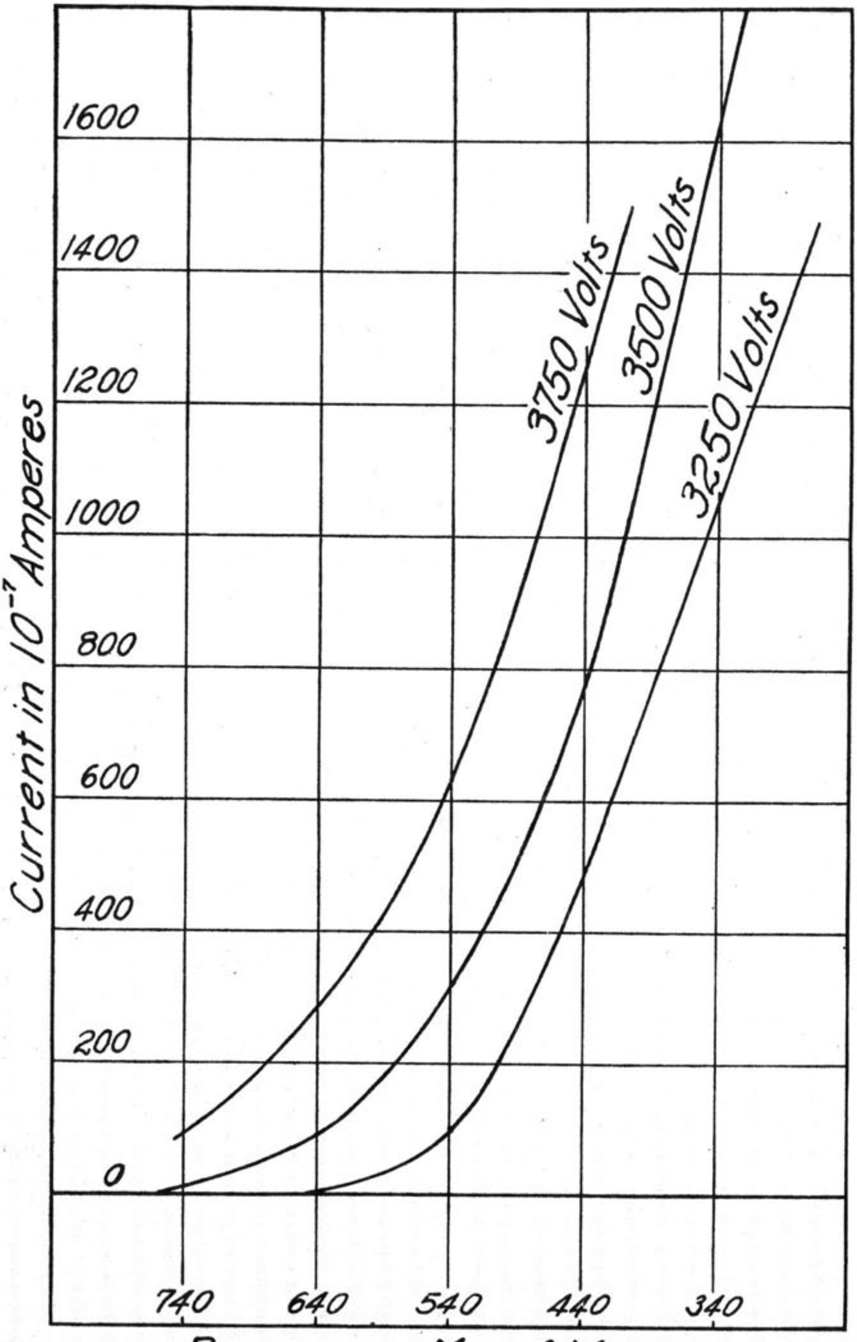

FIG. 46. CORONA CURRENT AS A FUNCTION OF PRESSURE IN HYDROGEN, WITH CONSTANT VOLTAGE AND WIRE POSITIVE

be ionized near the wire and still the resultant current be very small, for few of the ionized particles near the wire will pass through the space where there is a small gradient. Simple computations based on kinetic theory show that the maximum observed pressure increases can be explained by ionization if every molecule of the air within 1.39 millimeters of the wire is ionized. Within this distance the potential gradient is equal to the arcing gradient and it is therefore probable that all molecules are ionized.

27. *Further Verification of Kunz's Theory.*—The final equation as presented by Dr. Kunz is $ki = \frac{v_0}{e}(p_1 - p_0)\frac{1}{t} +$ a constant, where i is the corona current, v_0, the volume of the tube, e, the potential difference between the wire and the tube, $p_1 - p_0$, the pressure increase, k, a constant and p_0, the initial pressure. This equation shows that for a constant potential difference, e, the current, i, should increase as p_0 is lowered. Data were taken by measuring the current at various measured pressures, caused by a constant potential difference, which verifies this theory. These data are shown graphically in Figs. 46 and 47 when pure hydrogen and nitrogen respectively were the gases in the tube.

28. *Summary and Conclusions.*—Experimental results show:

(1) That the increase in pressure due to the corona appears and disappears much more rapidly than when due to heat only.

(2) That the heat in the corona discharge is not a prominent factor until many seconds after the corona appears.

(3) That in equal energy experiments the increase in pressure due to corona differs from the increase in pressure due to heat by nearly 50 per cent.

(4) That at the instant the corona appears the gas in the tube at a small distance from the wire is cooled.

(5) The ionization pressure in the positive corona is exactly proportional to the corona current in dry air, hydrogen, nitrogen, carbon dioxide, oxygen, and ammonia.

(6) Any chemical action that occurs because of the corona is proportional to the corona current.

(7) That the theory advanced by Professor Kunz is verified in one more field; namely, in the relation between current and pressure for constant voltage.

These results together with conclusions drawn from simple calculations force one to believe that the pressure increase in the corona

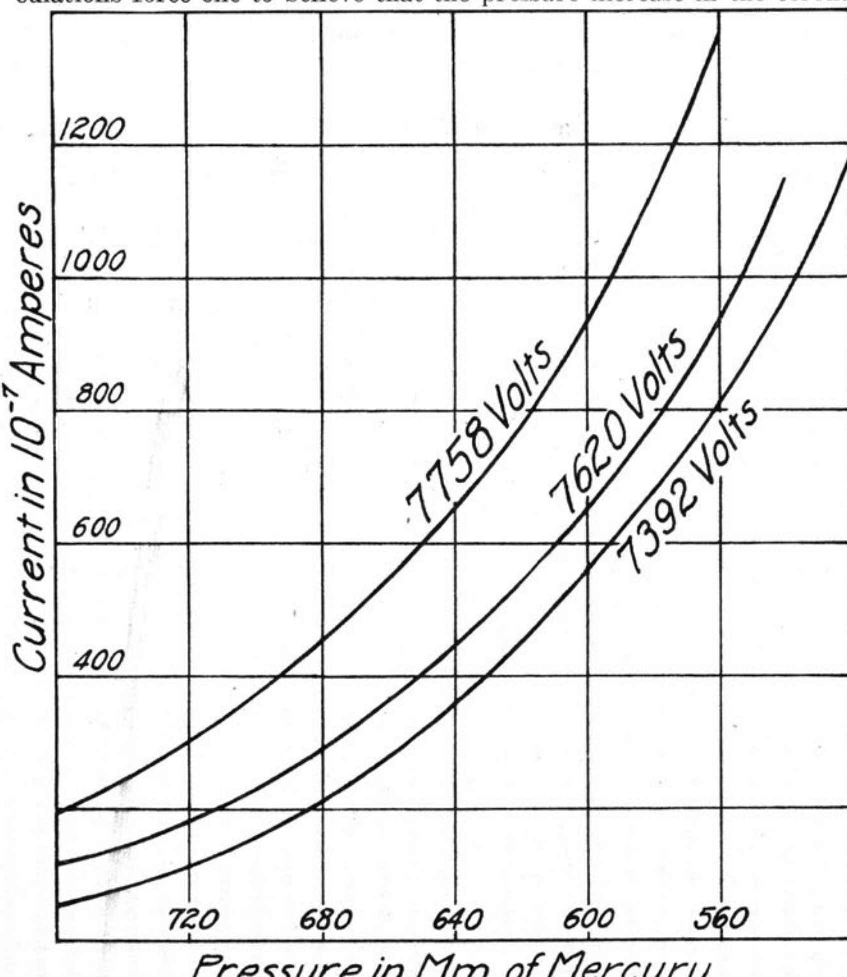

FIG. 47. CORONA CURRENT AS A FUNCTION OF PRESSURE IN NITROGEN, WITH CONSTANT VOLTAGE AND WIRE POSITIVE

discharge is not due to Joule's heat. With the knowledge of the distortion of the field in the corona tube it seems very possible that the increase in pressure is due to ionization.

Dr. A. M. Tyndall has also argued against a characteristic pressure effect in the corona. In his experiments he used a much smaller tube and introduced about one thousand times more energy per unit time than that used in these experiments, unless there is a misprint in the current (10^{-6} instead of 10^{-3}). Even if there were a misprint, the relative energy is still larger in Tyndall's experiments, because his inner wire was about thirty times smaller than those used in the measurements herein recorded. It is therefore possible that Tyndall observed only heat phenomena; moreover from his data it cannot be concluded that the pressure increase in question is proportional to the corona current, a fact which requires an explanation different from a simple heat effect. The cooling of the wire by the corona had been discovered in the Physics Laboratory of the University of Illinois before Tyndall published his paper. Tyndall's experiments cannot be considered conclusive; the characteristic pressure measured by Warner may be due to an increase in particles or to a partial vacuum surrounding the wire when the corona discharge takes place. The problem is not yet solved.

CHAPTER IX

Ozone Formation in the Corona

Among the problems attracting attention at the present time, that of the nature of the forces which hold the atoms together in the molecule is of great importance. The most probable suggestion is that these forces are due to the electrons and positive nuclei of the different atoms acting on each other according to laws still obscure. Most of the articles which have been published concerning this problem are of a speculative nature. If the forces are electrical, it seems obvious that some electrical method might be used advantageously in their study. Ionization, often followed by chemical reaction, is found to occur in solutions of electrolytes and sometimes in gases. A tremendous amount of work has been done with electrolytes in solutions of various solvents. These studies have led to the development of many interesting relationships, but there are so many complications in any study of liquid solutions that it is difficult to get much conception of the fundamental intramolecular forces. In spite of the fact that a much greater amount of work has been done on ions in solutions than on gaseous ions, more is known about the latter. In gases the ions have greater freedom of movement than in liquids. The structure is simpler and it is much easier to control and alter conditions. Ionized gases with charged atoms and molecules are often capable of causing chemical action and so may well lend themselves to the study of those forces which bind the atoms together. To cause a reversible reaction like $N_2 + O_2 \leftrightarrows 2NO$, for instance, to shift toward the right by purely thermal means would require a very high temperature for appreciable yields, but with the ionization of gases resulting from various forms of electrical discharge, similar yields can be secured at far lower temperatures. It seems probable, then, that the presence of ions in gases is the cause of new combinations of the atoms, but it might be that ionization is only an accompanying effect, not the cause of chemical reactions. It is very desirable when studying fundamental relationships to work with conditions as little complicated as possible. For this purpose there is available one reaction that involves the presence of only one element, oxygen, which is changed into ozone under suitable conditions.

The following is a discussion of the theory of ozone formation which is applied to the various known types of ozone formation: the oxygen atom is supposed to possess six electrons in the outer shell. The two atoms in the molecule may be held together in two different ways, between which there may be several gradations. The oxygen molecule may be represented by either of the formulas A, $:\ddot{O}:\,:\ddot{O}:$ or B, $:\ddot{\underset{\cdot}{O}}:\ddot{\underset{\cdot}{O}}:$. In the first form the atoms are held together by two valence bonds while in the second there is only one bond, each atom possessing an extra, unsatisfied valence. It is supposed that a valence bond is due to the coupling together of two electrons which tend to make a fairly stable union. In form B each atom has an extra unbalanced electron, and an arrangement exists similar to the usual conception of the ethylene molecule. In its second form the oxygen molecule would be highly reactive as, indeed, oxygen is well known to be.

If a neutral oxygen atom came in contact with form B, there would be a strong tendency to form the neutral molecule of ozone,

$$\begin{array}{l} :\ddot{\underset{..}{O}}:\ddot{\underset{..}{O}}:. \\ \,:O: \end{array}$$

The electrons not being symmetrically placed about the nuclei a strain results so that ozone is in an unstable condition and readily tends to decompose. The heat of decomposition of ozone by direct measurement is about +34,000 calories. This value is the resultant of the force required to split two extra atoms from two ozone molecules and of the force with which these two atoms unite to form a molecule, regardless of the order in which these steps may occur. It seems likely that an atom would have to come in contact with the unsaturated form of molecule B at just the right angle and with a suitable velocity in order to produce ozone. Collision between two atoms would result in the formation of a molecule with consequent degradation of energy as heat.

Apparently the formation of ozone requires oxygen atoms which may be derived from molecular oxygen or from some compound of oxygen with other elements. On this basis, in accordance with the mass-action principle, any factor which increases the atomic oxygen concentration ought to raise the yield of ozone.

Ozone is formed in many chemical reactions. The practical method for the manufacture of ozone is to pass air through some form of silent discharge. Whenever ozone is formed by means of an electrical discharge, light is produced. Indeed ultraviolet light of sufficiently short wave length produces ozone. It is possible that it is the light which produces the ozone even in the silent discharge and in the corona discharge. The vibrations of the ultraviolet light tend to loosen the oxygen bonds, to produce polarization at first and finally to cause dissociation of the atoms analogous to the thermol action of high temperatures.

The formation of ozone is an end of thermic reaction. At ordinary temperature ozone decomposes into oxygen, but the rate of decomposition is slow. The velocity of decomposition increases very rapidly with increasing temperature, so that for practical manufacture of ozone the gas should be as cold as possible.

For the formaton of ozone atomic oxygen seems to be required; the atoms may or may not be changed and this is a very important question.

The chemical reaction may be written in the form $O_2 - O \rightleftarrows O_3$. The heat of decomposition of ozone is about 34,000 calories. Ozone is, therefore, in a metastable condition at ordinary temperatures.

For the ozone formation in the corona discharge the following method and arrangement were chosen. The oxygen was prepared by electrolyzing a 20 per cent solution of sodium hydroxide with nickel electrodes. To remove hydrogen the gas was passed over heated copper oxide. Any carbon dioxide was removed by a 20 per cent sodium hydroxide solution in a bead tower. The gas was dried

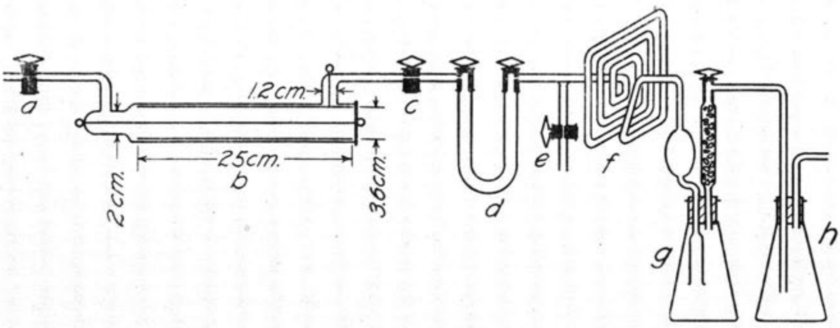

FIG. 48. DIAGRAM OF APPARATUS FOR THE STUDY OF OZONE FORMATION IN THE CORONA

by being passed through another bead tower containing concentrated sulphuric acid, through a large U tube filled with pieces of fused potassium hydroxide and finally through another large U tube full of phosphorous pentoxide. The corona tube was of glass; its dimensions are given in Fig. 48. The outer electrode was a sheet of gold foil 0.15 mm. thick. Connection was made by a platinum wire sealed through the glass and passing all around between the foil and the glass tube. A slit was left in the foil so that the discharge might be observed. It had the characteristic appearance for this form of discharge as described previously in this bulletin. The procedure was to fill the tube with pure oxygen, close the stopcocks and subject the enclosed volume of air to the discharge for varying lengths of time. The gas was then passed through neutral 2 N potassium iodide. The iodine set free was titrated with 0.025 N thiosulphate solution after acidifying with sulphuric acid. During the discharge the current strength was measured by a suitable galvonometer and was main-

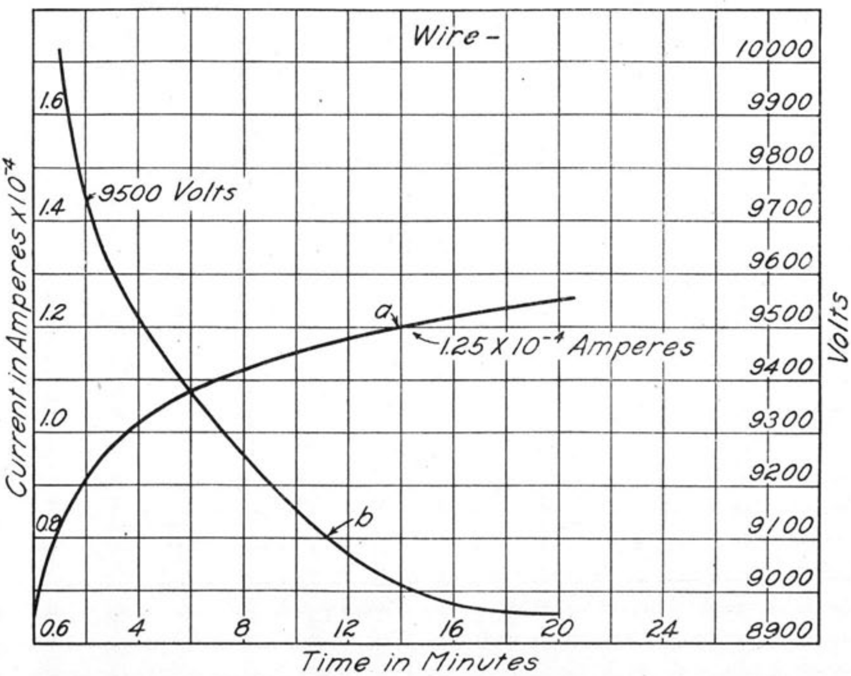

FIG. 49. INCREASE OF VOLTAGE AT CONSTANT CURRENT AND DECREASE OF CURRENT AT CONSTANT VOLTAGE IN THE FORMATION OF OZONE IN THE CORONA

tained constant by increasing the voltage as required. The resistance of the gas rises with the length of time of the discharge. The required increase in voltage due to the increased resistance is an exponential function of the time

$$V_t = V_0 e^{at}$$

V_0 is the initial voltage, V_t is the voltage at any time t, and a is some constant. This relation is well illustrated in Fig. 49, curve *a*. On the other hand if the voltage is maintained constant, the current strength will decrease as in Fig. 49, curve *b*. The formula for this hyperbolic curve will be somewhat like the other formula but with a negative exponent. An explanation of this phenomenon is given later. The state of affairs in the discharge is somewhat complicated. When the current is turned on, there is a slight immediate rise in pressure due to the ionization of the gas. This increase in pressure means a splitting of the molecules into atoms so that the total number of particles in the gas is increased. The oxygen atoms formed in oxygen unite chiefly with oxygen molecules to form oxone with a consequent decrease in volume which may be followed by a suitable manometer. The most (90–97 per cent) of even the initial energy is degraded into heat energy. As the ozone increases in concentration more of it decomposes with the liberation of more heat. All this heat causes an increase in the velocity of the molecules and an increase in the volume of the gas. The decrease in volume, which is a resultant of the ozone and heating effects, should bring about a decrease in resistance. The increased velocity of the molecules should also help to lower the resistance. Both of these effects should allow the easier passage of the ions through the gas. The explanation of the increase in the resistance is the counter electromotive force or polari-

TABLE 5

CURRENT-VOLTAGE RELATIONSHIP

Wire Positive		Wire Negative	
Amperes $\times 10^{-4}$	Volts	Amperes $\times 10^{-4}$	Volts
2.00	7910– 8300	1.25	8960–9550[1]
2.77	8960– 9260	2.50	9880–10280
3.75	9370– 9650	3.75	10400–10600
6.25	9680–10440	5.00	10800–11240
		7.50	11600–12480

[1] Cf. Fig. 49, Curve *a*

zation effect exerted by the ions present. As long as the tube is closed its size is the limiting factor. After a condition of equilibrium is once reached throughout the tube, the voltage required to maintain a certain amperage should be constant. The ionic equilibrium like the ozone-oxygen equilibrium depends upon diffusion to a large extent and this in turn is governed by the size and shape of the tube.

These data are the extreme values observed during a 20-minute run. To test the reproducibility of the method, runs were made during two different days with all the conditions as nearly constant as possible. Each run lasted just three minutes. The current strength was maintained exactly at 2.77×10^{-4} amperes and the wire was posi-

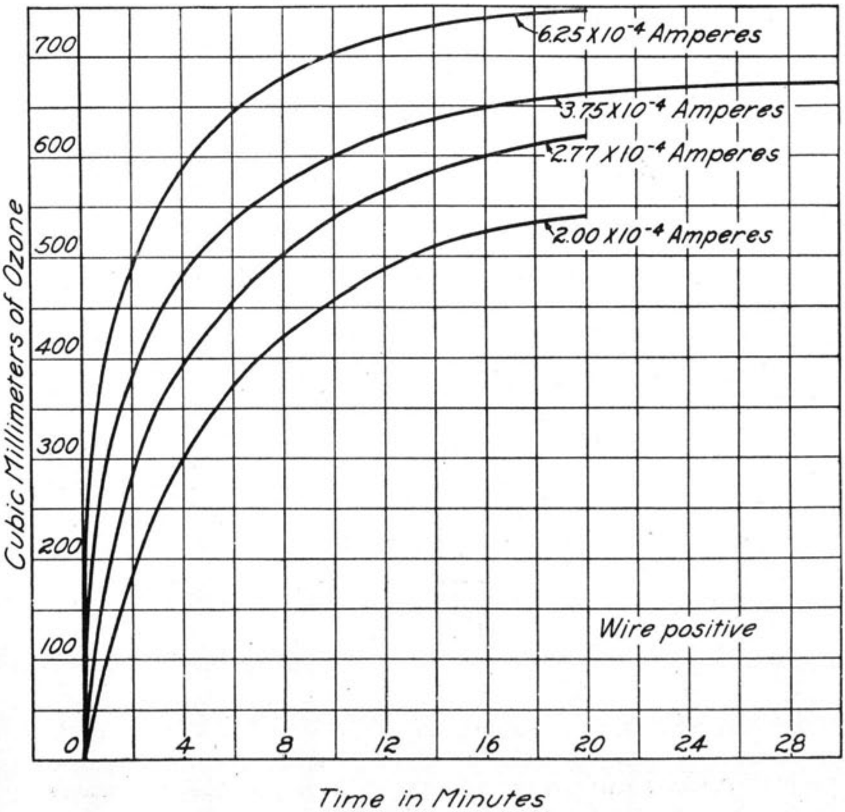

FIG. 50. OZONE FORMATION IN THE CORONA TUBE AT VARIOUS CURRENT STRENGTHS WITH WIRE POSITIVE

tively charged. The results were 345, 340, 335, and 360 cu. mm. of ozone. This corresponds to nearly 6 g. per kw. hr., a value lower than the values given hereinafter; for here the deozonizing effect of the discharge is considerable. To calculate the yield in terms of percentage divide the value in terms of cubic millimeters by 3000.* The results plotted in Figs. 50 and 51 represent all the results obtained with the amperage at a constant value and with no arc in series. The following yields have been calculated from measurements of the initial slopes of these curves.

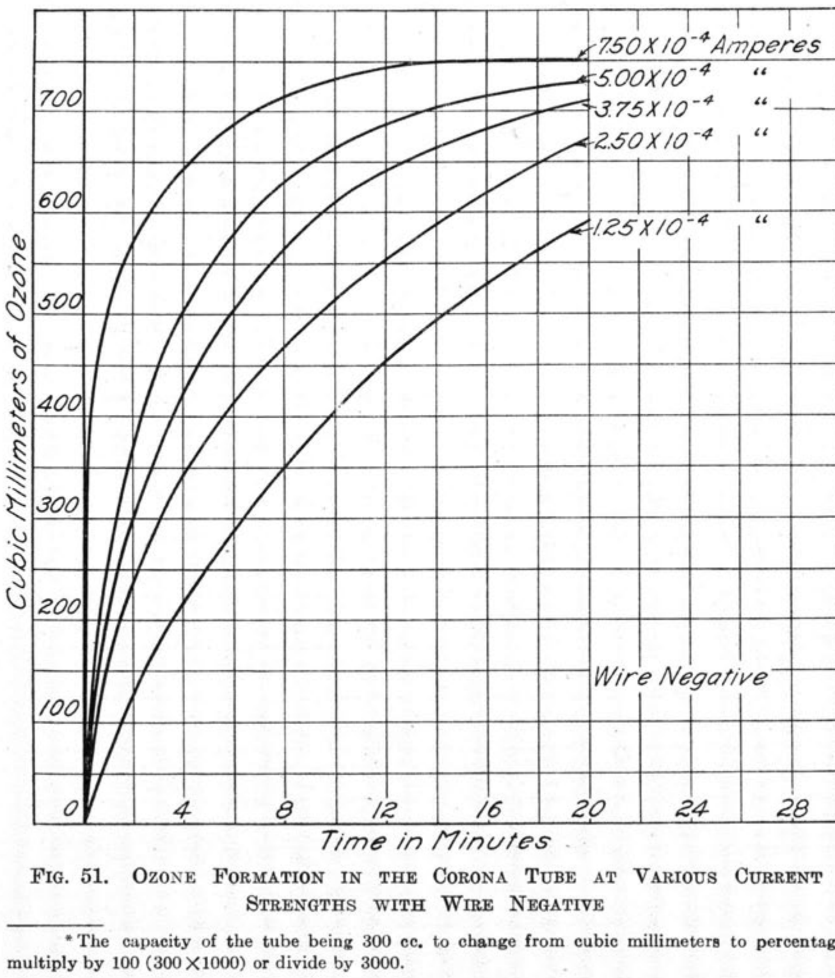

FIG. 51. OZONE FORMATION IN THE CORONA TUBE AT VARIOUS CURRENT STRENGTHS WITH WIRE NEGATIVE

* The capacity of the tube being 300 cc. to change from cubic millimeters to percentage multiply by 100 (300 × 1000) or divide by 3000.

TABLE 6

OZONE YIELDS CALCULATED FROM THE INITIAL SLOPES OF THE CURVES IN FIGS. 50 AND 51

Wire Positive Grams of Ozone per Kilowatt Hour			Wire Negative Grams of Ozone per Kilowatt Hour		
Amp. $\times 10^{-4}$	Without Spark	With Spark	Amp. $\times 10^{-4}$	Without Spark	With Spark
2.00	7.7	13	1.25	13	22
2.77	12.7	18	2.50	14.1	23
3.75	20.7	29	3.75	14.2	25
6.25	23.3	..	5.00	11.3	..
....	....	..	7.50	24	..

These values are being checked by passing the gas through the discharge at various speeds. With the wire charged positively, about the same amount of ozone is formed as with the wire charged negatively. This result does not agree with either Warburg* or Cermak† who working with a point discharge and influence machine current observed the ozone concentration with the point negative to be about three times the concentration when the point was charged positively. Their explanation was that the greater speed of the negative ions was responsible. This seems to be a reasonable explanation, but these curves show that there is something more to be taken into consideration. The point discharge, especially with an influence machine supplying the current, is very complicated. The curves in Figs. 50 and 51 belong to a family of parabolic curves which tend to approach a common point as a limit. The general formula for these curves is,

$$y=a\,t^{n}$$

where y is the yield of ozone, a is a constant, t is the time, and n is a fraction between 0 and 1. The greater initial slope of the larger current curves indicates that there is a greater ozonization, but the smaller slopes of these curves after five minutes show that there is also a very much larger deozonizing effect. The resultant is probably the same in all cases with an electrical equilibrium formed. This electrical equilibrium for any one apparatus and source of power is probably independent of the current strength. It is the resultant of the ozonizing and deozonizing effects of the current and the small spontaneous decomposition of ozone at the temperatures (24 ± 3 degrees) and pressures (740 ± 5 mm.) used.

* Ann. Phys., Vol. [4] 9, p. 781, 1902.

† Ber. deut. physik. Ges., Vol. 4, p. 268, 1906.

A few experiments were made with a spark gap in series. The spark was between two 1 cm. zinc spheres which were adjusted by a micrometer screw. The effect of an arc in series with the corona has been studied by Crooker.* He showed that the effect is not to produce an oscillating but an intermittent direct current. In Table 6 some yields are given of ozone per kilowatt hour. These were calculated as follows: With the wire positive and with the current of 2.00×10^{-4} ampere, the yield of ozone was two-thirds greater for the three-minute interval with rather than without the spark in series. The increases are greater for the smaller current strengths. These results throw some light on the effect of alternating or fluctuating current and of different frequencies on ozone production. This point will be discussed later in connection with the further study of ozone formation in the corona which is being continued in the Chemical Laboratory of Purdue University.

*Crooker, Am. J. Sci., Vol. 45, p. 281, 1918.

CHAPTER X

The Influence of a Series Spark on the Corona

The typical positive corona discharge is a uniform glow around the wire, while the negative corona consists in more or less evenly spaced bright beads. If a short spark is included in series with the corona tube, this difference in the discharge is largely eliminated, the discharge appearing almost the same whether the wire is positive or negative. The introduction of the spark in series entirely changes the visual character of the corona glow. The usual characteristic negative beads spread laterally and in diameter into a fuzzy glow (blue in air), whereas the quiet uniform positive glow gives place to a remarkable display of purple streamers shooting radially from the wire to the tube and at times completely filling the tube with light. These visual characteristics are essentially the same in all gases.

When this marked difference between the corona with and without the spark in series was first discovered, it was suggested that perhaps this difference was due to high frequency oscillations super-

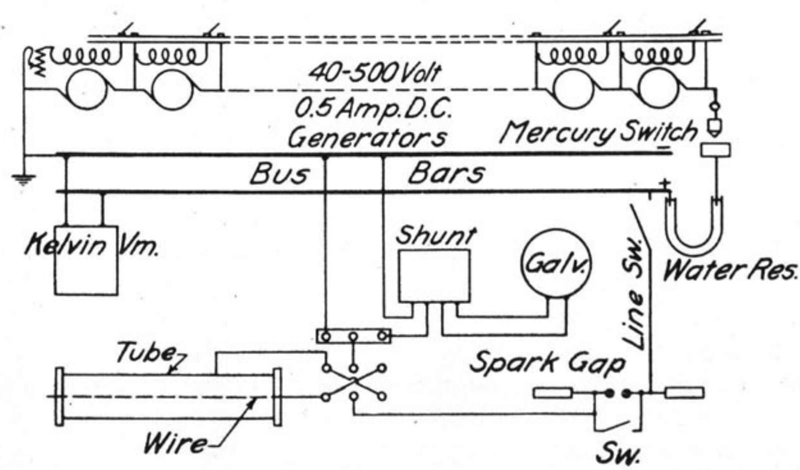

Fig. 52. Diagram of Connections of Apparatus for Study of Influence of a Series Spark on the Corona

imposed upon the direct-current phenomenon. The results presented in the following pages of this chapter comprise the present knowledge of this peculiar corona phenomenon.

29. *Apparatus.*—The electrodes of the spark gap were polished brass spheres, one centimeter in diameter, fastened to brass rods which were supported by hard rubber blocks on a solid hard rubber base. One of the electrodes was supplied with a micrometer screw and an insulated handle which permitted an easy adjustment of the spark discharge. This spark gap was connected in series with the self-opening line switch and the corona tube through a reversing switch which allowed quick reversal of the polarity of the axial wire. The connections of the apparatus are shown in Fig. 52.

30. *Visual Characteristics of the Corona with Spark in Series.*—If in positive corona a short spark is placed in series with the corona tube, containing air at atmospheric pressure, after the voltage is high enough to give a bright uniform glow a most remarkable change takes place in the discharge. For very short sparks a few bright purple radial pencils or streamers of light will shoot out irregularly from the wire toward the tube. These streamers increase in number and in brightness as the spark gap is opened and may at times completely fill the tube with purple light. They are brighter and more easily formed at the higher pressures and at voltages slightly above that for the starting glow, but they have been observed at pressures as low as 30 cm. of mercury.

The same changes in the appearance of the positive glow by the introduction of a series spark have been observed in illuminating gas and hydrogen. The uniform positive glow is in both cases transformed into the radial streamers by the action of the spark. In illuminating gas these streamers are of an intense blue-green color, while in hydrogen they are of a milky white or silvery appearance.

In negative corona a short series spark has the effect of destroying the characteristic negative beads. Introducing a very short spark reduces the clear beads in brightness and in their clear-cut form, and they become hazy at the boundaries. Gradually opening the spark gap causes a slow transition of the beads from the clear intensely concentrated form of glow to a uniform fuzzy glow which spreads laterally from the beads along the wire and which is slightly larger

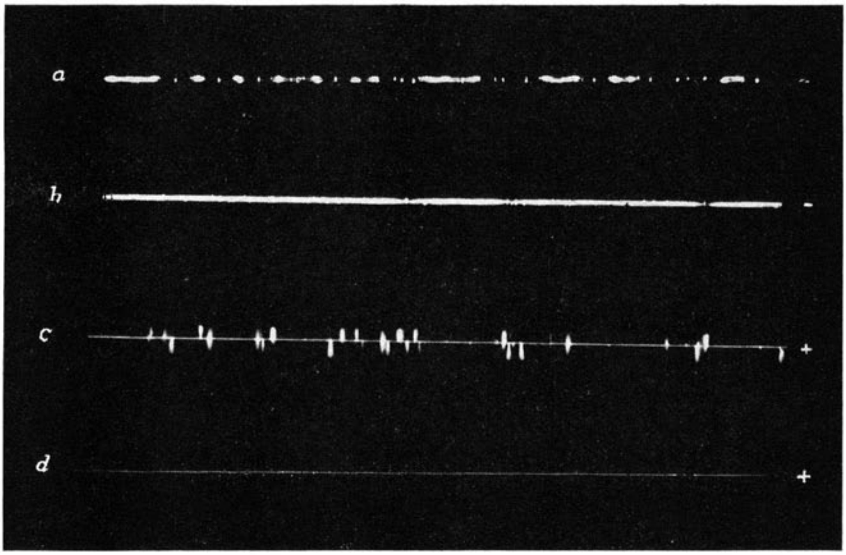

Fig. 53. Corona Discharge with and without a Series Spark

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in diameter than the original beads. The bright cores of the beads maintain their positions until the last, although they are greatly reduced in intensity and may even be seen when the spark gap is so long that the glow flashes but intermittently. The characteristic destruction of the clear form of the beads due to the action of the spark has also been observed in illuminating gas and in hydrogen at various pressures. The appearance of the glow remains the same, whether the spark is placed on the grounded side of the tube or on the high potential side.

Photographs of the corona discharge with and without a series spark are shown in Fig. 53.

31. *No Oscillations in the Corona.*—When the influence of the series spark was first discovered, the action was attributed to oscillations or surges started in the system by the spark. This suggestion was made, because when a 2 micro farad condenser was placed in parallel with the tube and the wire, the hazy, beaded discharge appeared for both positive and negative corona, and did not change in character when a series spark was added to the circuit. When the spark is placed in series many times, a hissing sound is heard which might be due to oscillations.

To determine whether the series spark sets up oscillation several experiments have been performed. The results, which show that oscillations are not present, will be given in the following paragraphs.

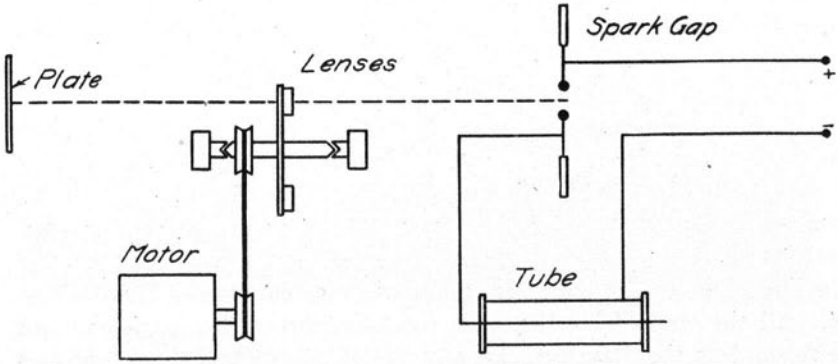


FIG. 54. ARRANGEMENT OF APPARATUS FOR BOYS'S METHOD

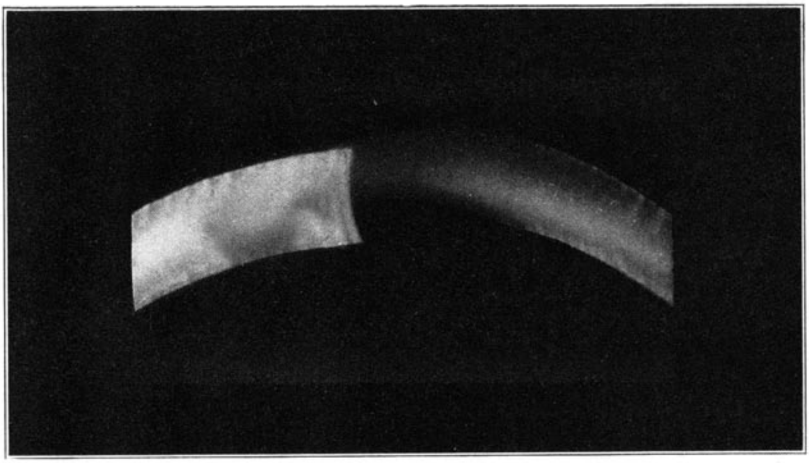
The difference between the positive and negative corona with series spark, as described, is so conspicuous as to exclude the possibility of the effect being due to oscillations. If there were oscillations, they could not be symmetrical with respect to the time axis.

The oscillograph and vibration galvanometer cannot be used to determine the current wave form, because the currents are too weak to overcome the inertia of the moving elements. Three methods have been used which give accordant results: the telephone, revolving lenses and a photographic plate, and a cathode tube with a hot lime cathode. The last method may be made very sensitive and gives satisfactory results.

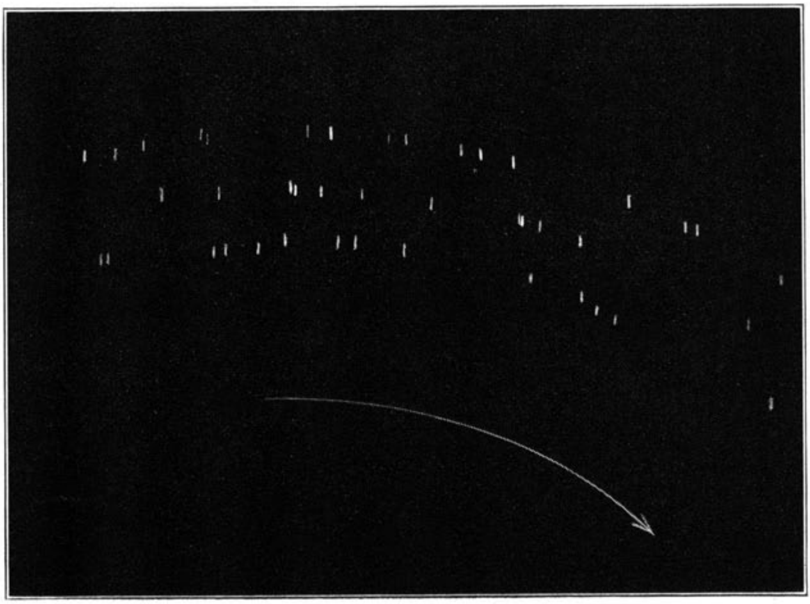
In the telephone receiver method a receiver connected in parallel with a resistance was used in place of the galvanometer. The passage of the faintest spark can be detected. When the voltage is high enough to produce corona, a sharp click is heard in the telephone as each consecutive spark passes and a flash of glow appears on the wire in the tube. If the sparks pass in very rapid succession, the glow will appear to be practically continuous. The discharge between the spheres is intermittent and forms a white line in the gas.

The corona tube acts like a condenser charging and discharging at intervals, according to the length of the spark gap. It can be arranged so that for long sparks only one spark passes per second or for short sparks several thousand pass per second, and as each spark passes it will register a sharp click in the telephone receiver. Decreasing the spark length from the longest sparking distance will make the sparks jump faster and faster until for very short spark lengths the sound in the telephone practically passes from the audible range. The results obtained with the telephone suggest the assumption that the corona current with a spark in series is only intermittent and not oscillatory.

Boys's method consists in photographing the spark directly when the image from it sweeps across a photographic plate. Boys (19) used a system of six revolving lenses set in one solid disc. Each lens was mounted a little offset from the center of the disc as compared with those adjacent, so that the image from it would not overlap the others. The arrangement of the apparatus is shown in Fig. 54. All the lenses have the same focal length; so the spark gap can be focused on the plate through any one of them. The spark gap and the photographic plate are stationary, but since the lenses move, the



a



b

FIG. 55. PHOTOGRAPHS OF OSCILLATORY AND UNIDIRECTIONAL SPARKS

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focus of the spark shifts from one point to another across the plate leaving its record of instantaneous images.

A small motor drives the lenses at a speed of about 6000 r. p. m. The lenses are set about four inches from the center of the disc so that it is possible to get a linear speed of approximately 100 ft. per sec. across the face of the photographic plate.

By this method it is possible to analyze the spark and to determine whether it is of an oscillatory or unidirectional character. An oscillatory spark will give an irregular band of light across the plate (see Fig. 55*A*), while a unidirectional spark leaves only a sharp line (see lines in Fig. 55*B*).

For rough determinations it is easy to observe the image of the spark on the ground glass plate and to find quickly if the spark is oscillatory or not. If it is oscillatory, one can observe the approximate frequency and duration of the spark. For more nearly accurate determinations photographs must be made on sensitive plates and observations and measurements made from them.

Several observations were made with this method for various spark lengths and speed of lenses using both air and hydrogen in the corona tube. In the first experiment corona was produced in air at a pressure of 500 mm. by a potential of 14,000 volts. The spark gap was about 1.5 mm. in length and the lenses were driven at a speed of 2,000 r. p. m. A photograph was taken, but the individual sparks showed no trace of being oscillatory.

To spread out the individual spark images the lenses were driven at the higher speed of 6,000 r.p.m. and the spark gap set at 1.19 mm. This arrangement allowed a passage of nearly 2,500 sparks per second and a speed of about 100 ft. per sec. across the plate. The half-tone, Fig. 55B, clearly showed that the sparks were not of an oscillatory character but unidirectional, that only a sharp line was recorded as each spark passed, and that the duration was less than 1-100,000 second. Each spark was, moreover, a little brighter at the negative electrode, and showed that all the sparks passed in the same direction and were of the same character.

With hydrogen in the tube at a pressure of 744 mm. and a potential of 9,400 volts photographs were taken when the spark gap was 0.75 mm. and 0.3 mm in length. For the 0.75 mm. gap the frequency of the sparks was about 10 per second and produced a large number of silvery streamers in the corona tube. When the gap was reduced to 0.3 mm., several hundred sparks passed per second and the corona tube was completely filled with streamers. In every case the sparks were unidirectional, sharp and clear-cut, and showed no oscillatory character whatever.

To determine the form of the current curves when the spark is in series a special hot-lime-cathode Braun tube was designed and constructed as shown in Fig. 56.

A narrow platinum strip, P, fastened to the insulated brass blocks, B_1B_2, is heated by an auxiliary current passing through the leading-in conductors, C_1C_2. A small spot of calcium oxide placed upon this heated strip has a peculiar property of giving off a stream

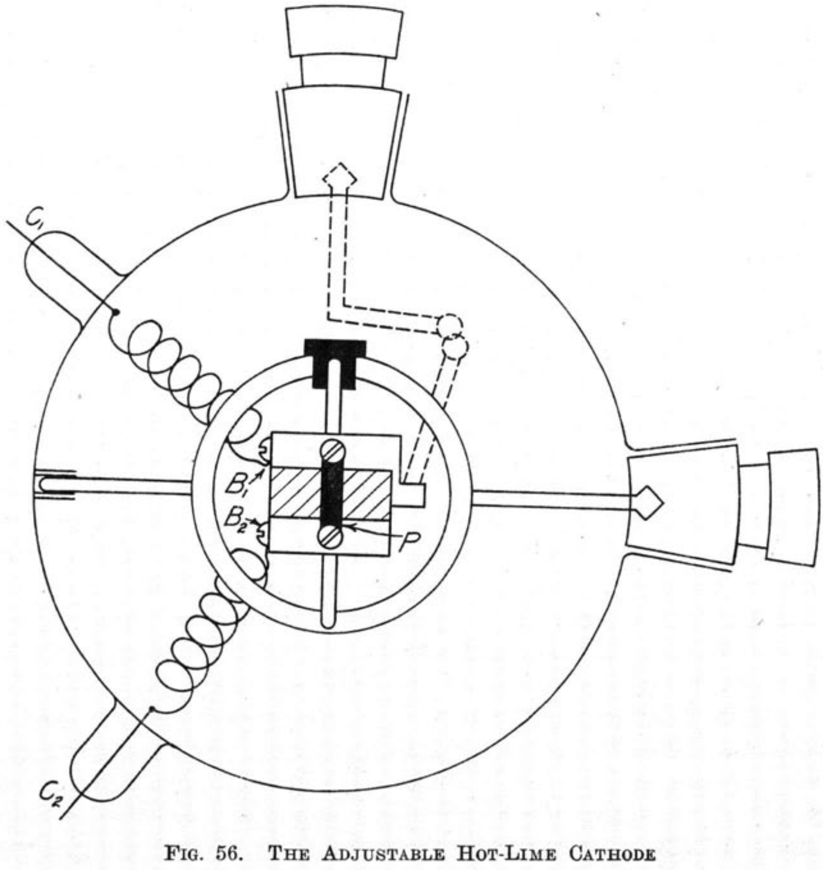

FIG. 56. THE ADJUSTABLE HOT-LIME CATHODE

of slow moving electrons when used as cathode in a discharge tube at a very low pressure. It is necessary to use only a low potential of nearly 400 volts between anode *A* and cathode *C*. The block holding the platinum strip was mounted upon a gimbal support, as shown, in order that the soft cathode beam could be easily adjusted through a hole in the diaphragm, *D*, fall upon the fluorescent screen, *S*, and there produce a spot of maximum brightness. This double adjustment is necessary, for it is impossible to assure by construction the exact direction of the beam.

If a very weak magnetic field is placed at right angles to this beam of slow moving electrons, the beam will be deflected and the bright spot shifted on the fluorescent screen. When the magnetic field is alternating or pulsating, the rapidly moving spot will cause a line to be seen on the screen. If this line is observed in a mirror rotating at right angles to it, the line is spread out into a curve representing the variations in the current of the coil which excites the magnetic field.

The coil used had about 3,000 turns of No. 26 enameled copper wire wound in two sections and mounted so that it could be fitted closely to the neck of the tube.

It might be advantageous to note briefly some of the details necessary in constructing and operating the hot-lime-cathode Braun tube.

(1) The cathode should be adjustable in order to get a spot of maximum brightness.

(2) A diaphragm, D, is necessary to eliminate extraneous light from the hot platinum strip and to stop down the divergent cathode beam.

(3) The cathode should be as near the fluorescent screen as the sensitiveness of the apparatus permits.

(4) CaO mixed with a small quantity of $BaNO_3$ insures a longer life to the lime and may be easily applied as a paste.

(5) The anode should be near the cathode, for instance, 1 cm. distant.

(6) The potential may be as low as 300 volts and preferably from a constant source, as from storage cells.

(7) The pressure must be very low and may even be assisted with charcoal and liquid air. Gases are given off from

the lime cathode freely and necessitate constant pumping if the tube is to be used for any length of time.

With this hot-lime-cathode apparatus it was easy to observe in the rotating mirror the forms of the current curves when a spark passed and when the current flowed through the corona tube. The field coil was connected in series with the circuit: (1) between the spark gap and the corona tube, and (2) between the corona tube and ground or negative terminal of the generators (see Fig. 52). The current forms are sketched in Fig. 57 as they were observed in both of these positions and for the conditions (N) when there was no spark, (S) when sparks were passing slowly, and (F) when sparks were passing rapidly.

With the coil in the position (1) and with no spark, the current, N_1, was observed to be a unidirectional one with an irregular and ragged edge. These irregularities are noticeable and are probably due to poor commutation at the machines as well as fluctuations in their speed of rotation.

With a few sparks passing, for instance, three per second, the current, S_1, suddenly jumps to a maximum each time a spark passes and then more gradually falls to zero. The current is always in one direction and its maximum value is larger than N_1.

When the spark gap is adjusted so that sparks pass more rapidly, the current, F_1, has the same shape as S_1 except that the impulses are crowded closer together.

With the field coil connected in the position (2), without spark, the current, N_2, is constant and gives a straight line.

With only a few sparks per second a peaked current form, S_2, rises rapidly and decays more slowly than in S_1.

For a greater frequency of sparks the ionization comes into play in a more pronounced fashion. The ionization current does not have time to reduce to zero between consecutive impulses from the spark, and so the resultant effect is a direct current, F_2, ordinarily called a pulsating current, with peaks that correspond to the sparks passing on the other side of the tube.

These current forms are essentially the same both when the wire is positive and negative. They show directly that there are no oscillations in the series spark nor in the corona tube. If there were surges or oscillations left, they would have to be exceedingly weak and

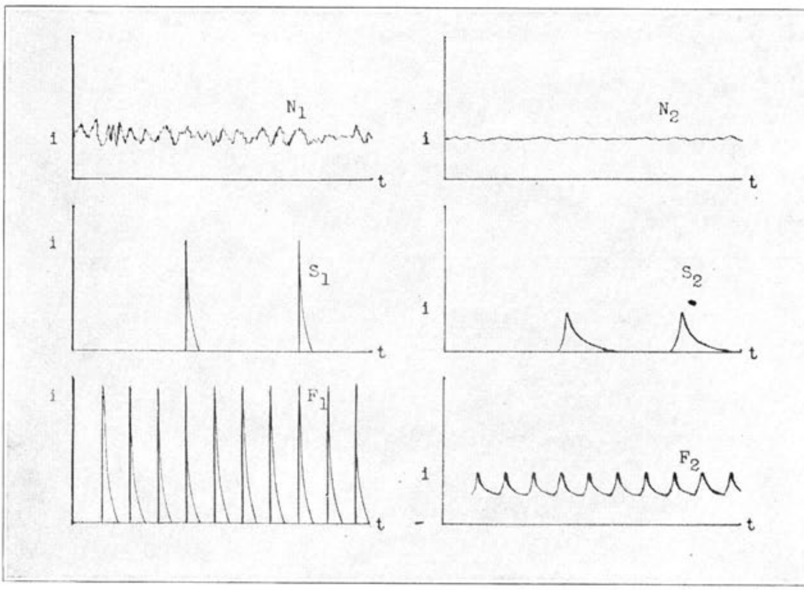

FIG. 57. CURRENT FORMS IN THE SPARK AND CORONA TUBE

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of very high frequency. The results of these three methods show conclusively that the corona current with a spark in series is only intermittent and not oscillatory.

32. *The Corona and the Arc.*—Electrical discharges in gases at pressures near that of the atmosphere may be divided into five classes. These are:

(1) The dark discharge, where a small current passes through gas without making itself visible.

(2) The glow discharge, where a larger current passes and the gas in the immediate neighborhood of the electrodes becomes faintly luminous.

(3) The brush discharge, such as that from points where the glow is irregular and extends into the gas some distance from the electrodes.

(4) The spark discharge, which is a transient phenomenon bridging the whole distance between the electrodes, accompanied by a bright light and a comparatively large current.

(5) The arc, in which a large current passes between the electrodes in the gas and the ionized vapors of the electrodes producing a continuous light.

Any one of the first forms of discharge may be converted into any one of the latter forms by an increase in the potential between the electrodes, depending upon the nature and pressure of the gas, and the spacing, size, capacity, and shape of the electrodes.

The corona may be classed as a glow discharge like the positive wire without a spark, or as a brush discharge like the negative beads or the positive streamers. This glow or brush discharge easily goes over into the arc, and in the following paragraphs this transaction will be considered.

It has often been observed that an arc easily forms in the tube when the line switch connecting the tube is opened, especially when the wire in the corona tube is positive and a fairly large current is passing in the discharge. The conclusions drawn from the available data are as follows:

(1) For a given configuration of electrodes the arc-over takes place as soon as the current has reached a certain value which is nearly constant for all pressures.

(2) Arc-over occurs at lower voltages for smaller wires.

(3) At low pressures arc-over for the negative wire occurs at less voltage than for the positive wire.

(4) At high pressures (near atmospheric) arc-over for the positive wire takes place at a less voltage than for the negative wire.

The water resistance connected between the generators and the main bus bar was replaced by a 0.5 ampere fuse in order to see if it had any effect on the corona discharge with and without a spark. The visual forms were studied with the coaxial cylinders (the inner one being No. 20 copper wire) as well as with parallel (No. 20 copper) wires as electrodes.

With the cylindrical electrodes the general results obtained showed that the usual characteristic visual forms of the corona discharge were not materially altered for positive wire or for negative wire with and without a series spark. The only noticeable change was an increased brightness in the positive uniform glow, streamers, and negative beads. With the water resistance cut out the available energy was increased about one hundred times or, in other words, to 10 kilowatts. The negative beads and the positive streamers while much brighter were also in a more agitated state than before the increase in energy. They moved rapidly back and forth on the wire and would go over into the arcing stage much easier than they would with water resistance connected. The axial wire was No. 20 copper tightly stretched, but it was easily set into violent vibrations, at 739 mm. pressure and 12,700 volts, within a few seconds after closing the line switch. The applied potential fluctuated at times as much as 100 volts and the result was a more unsteady discharge. The water resistance has the effect of damping out the smaller variations.

The ease with which the arc formed was also noticed in experiments with No. 20 wires strung parallel with each other, placed ⅛ inch apart and sealed into a glass tube.

With hydrogen it was noticed that when the wire was at a given potential above the critical glow voltage, the current in the beads would increase with the time, the beads would increase in size and in a short time would combine to form an arc. Detailed observations were made on this point.

After the switch was closed, several beads were formed which soon combined into one much larger and brighter, as shown in Fig. 58. This bead seemed to take hold on the wire at a surface irregularity and remained fixed. A bright reddish spot on the wire formed the base of the bead, while a bright blue-white core extended from this spot toward the bright spots on the edge of the observation slot and shaded off into a milky glow or brush. As time proceeded the core grew larger and brighter and the milky glow of the brush reached farther toward the tube, as in *B*. Soon a faint reddish glow, *C*, appeared in the gas, proceeded from the bright spots on the tube, and extended toward the bead. This glow continued to increase in

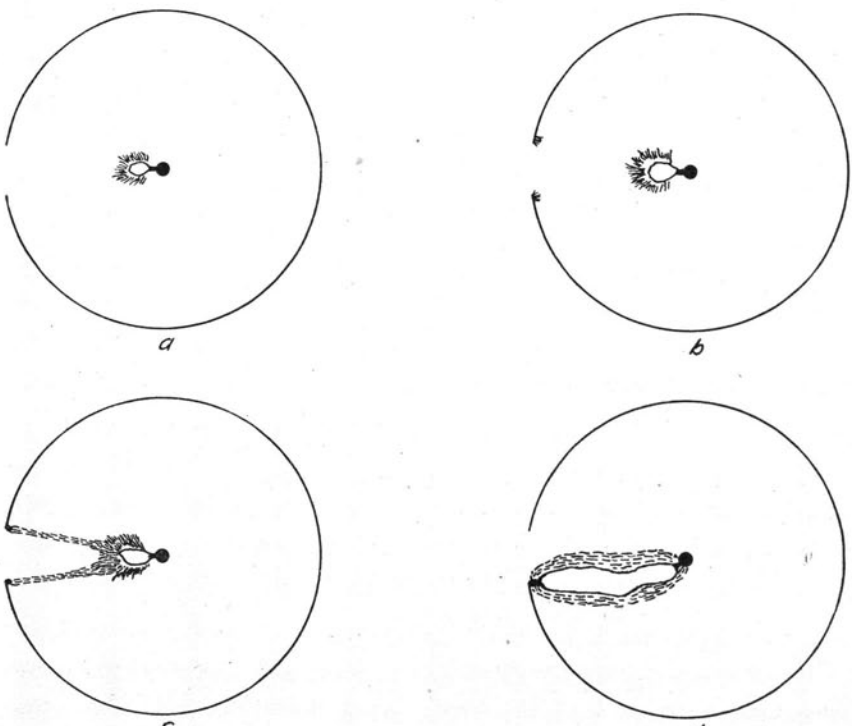


FIG. 58. EVOLUTION OF BEADS INTO THE ARC

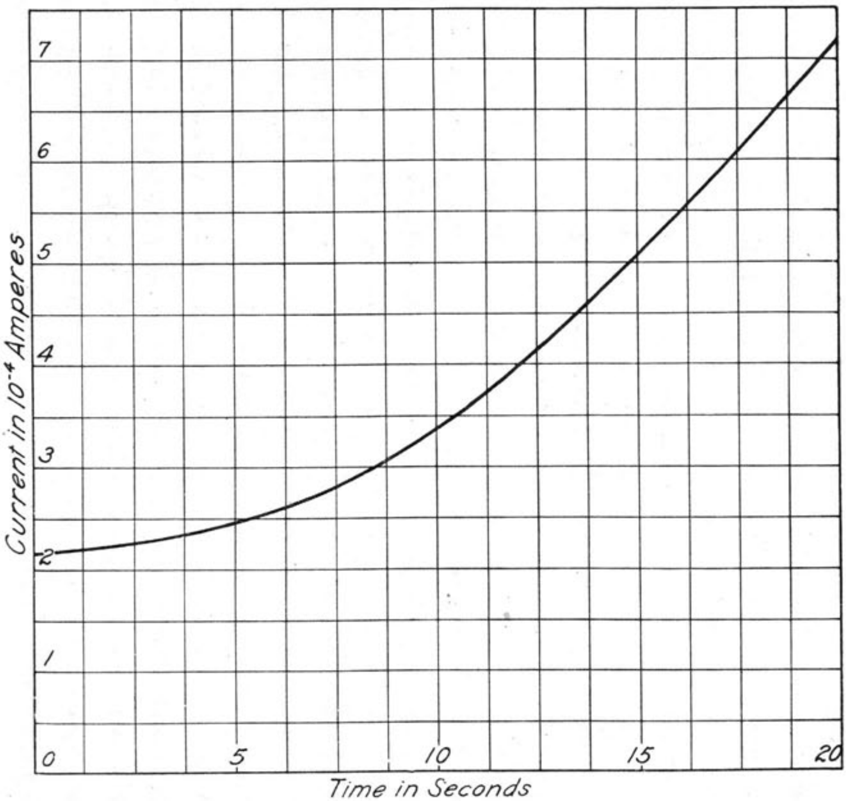


FIG. 59. CURRENT INCREASE WITH TIME FOR POSITIVE STREAMERS

brightness for a short time until the arc, *D*, flashed into existence. The arc had a very bright tubular blue-white core surrounded by a hazy reddish glow and extended from a bright reddish spot on the wire to bright white on the tube. The negative beads and perhaps the positive streamers may be spoken of as miniature or beginning arcs which unite to form a single arc when the current density reaches a certain value.

The curve in Fig. 59 will serve to show how the current in the streamers increases with the time. At a potential of 11,850 volts, somewhat above that for starting corona glow in air at 751 mm. pressure, a spark gap of 0.18 mm. length was placed in series with the tube. Readings of the current were taken at intervals of 5 seconds and when plotted resulted in the given curve. An arc passed shortly after 20 seconds, but the maximum current before it occurred was not obtained.

The increase of the current depends largely on the sparking distance and on the applied voltage (see curve *a*, Fig. 60). When the spark distance from zero is increased, the current for the positive corona decreases accompanied by a decreased brightness of the uniform glow, reaches a minimum value, and as the streamers appear rises to a maximum rapidly and falls off to zero for a large spark distance. The streamers are brightest at the maximum current value and are always connected with a large current. The corresponding negative curves show no such a maximum, with increasing voltage the positive current increases very rapidly.

In order to test the relative magnitude of the current due to the accumulation of ions and that due to the spark, a current-spark dis-

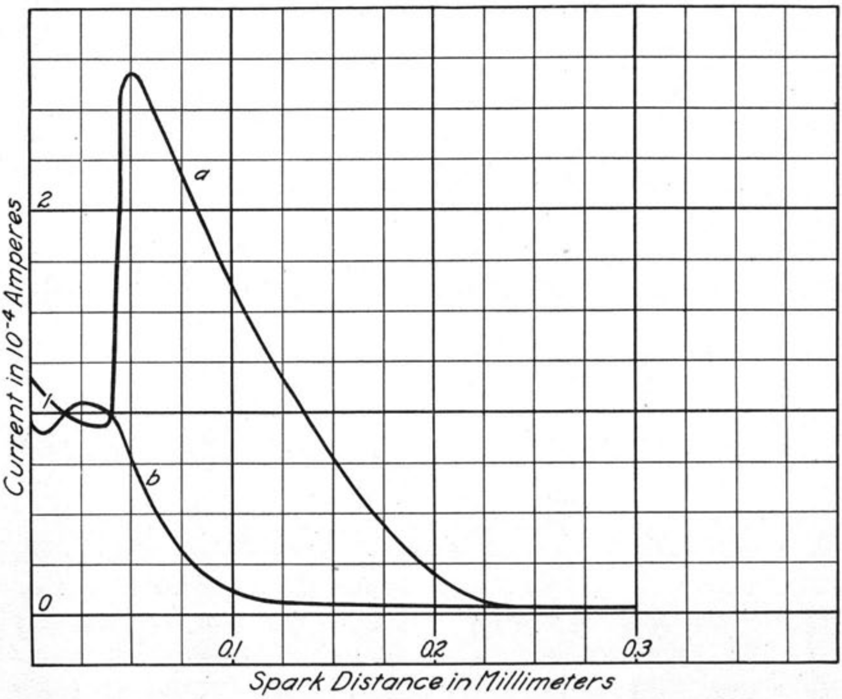


FIG. 60. CURRENT CHANGE FOR VARYING SPARK DISTANCE

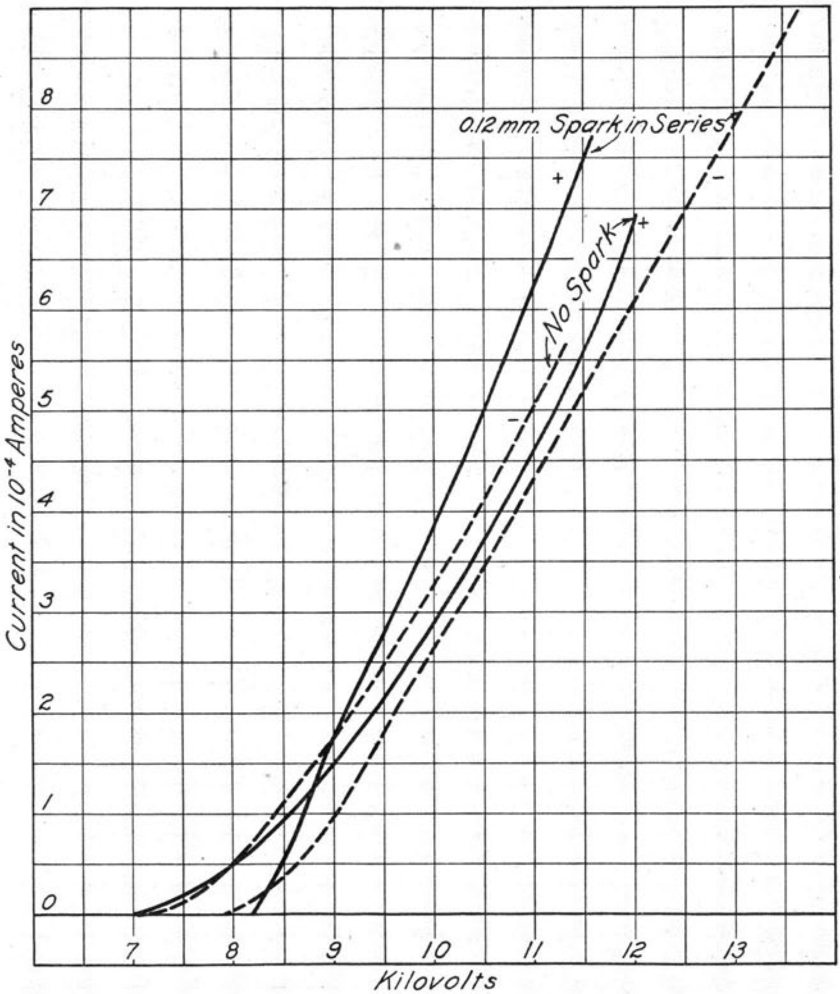


FIG. 61. CHARACTERISTIC CURVES WITH AND WITHOUT SERIES SPARK

tance curve was taken, when the tube was closed, and another when a small current of air was passing through the tube sweeping out some of the ionized gas.

The curves are given in Fig. 60, curve *a*, being taken with the tube closed using a potential of 11,850 volts, and curve *b* with a stream of air passing which necessitated a higher corona voltage; namely, 13,100 volts.

Curve b still has the characteristic maximum in the curve, but it is very much reduced in size, whereas curve a has a very pronounced maximum of a large value. These curves portray in a striking manner the effect a short spark has in producing a very great ionization in the gas, and also makes it easy to conceive how the positive arc takes place so readily when the switch remains closed for a little time or is suddenly opened while a large current is passing in the tube.

The ordinary characteristic current-voltage curves as obtained in the process of experiments without a series spark give the negative characteristic as lying above the positive. This relative position is maintained in all cases, with one or two minor exceptions.

When a short spark is placed in series with the corona, these positions are reversed and the positive curve lies above the negative, except at the starting point where the curves cross and give a lower starting potential for the negative wire (See Fig. 61). The starting potential with the spark in series is, however, higher than for the other case. It might be pointed out also that the characteristics taken with a series spark are more widely separated than those taken without, and thus they show a wider variation in the current from the positive and negative wires for a given voltage.

It was found when the spark gap was closed while current was flowing that the current would drop in a short time to a position on the ordinary characteristic curve. If the wire is positive at 11,000 volts and a 0.12 mm. spark is in series, for instance, a current of $6.2 \cdot 10^{-4}$ amperes will flow. Short-circuiting the spark gap will cause the current to drop to the value $4.6 \cdot 10^{-4}$ amperes which is a point on the ordinary positive characteristic curve. Similarly by short-circuiting the spark gap when the wire is negative the current will increase to a value which lies on the ordinary negative characteristic. These observations again show that the positive streamers carry a large current.

Without a spark gap in series with the tube, the ordinary uniform positive glow is formed by ionization in the gas near the wire where the field strength is greater than thirty kilovolts per centimeter, the current being carried by both positive and negative ions. The usual negative corona discharge begins critically as a uniform glow similar to that of the positive discharge but has a greater thickness. The brushes or negative beads, soon formed by a slight potential increase, bear a similarity to the arc. This fact, in addition to the position of the negative characteristic curves and to the influence which the surface condition and the material of the wires have on the beads, leads to the belief that an electron emission is present in addition to ionization by collision in the gas.

The case is somewhat different when a series spark gap is used. The corona tube may be considered as a leaky condenser connected in series with a spark gap and a constant source of high potential. A charge will build up to the condenser until the potential difference of the spark gap is sufficient to break down the air between the electrodes. An instantaneous unidirectional current will glow across the spark gap and at the same time the potential across the tube will increase to a point where the corona is formed. The current now passing through the tube will immediately reduce the potential of the spark gap below its critical point and the circuit will be broken. The process is then repeated.

The more nearly uniform appearance of the negative corona can now be explained as a super-imposed building-up and decay of the negative glow discharge through its different stages as the potential on the tube fluctuates. The positive streamers have at times been observed at critical voltages on rough wires when no spark was in series. These streamers are similar to the positive brush discharges observed from pointed electrodes maintained at high positive potentials. Their characteristic presence in the corona tube when a spark is in series is due probably to the sudden impression of a strong field and may be accompanied by a discharge of positive metallic ions, since it has been observed that the surface of the wire becomes disintegrated at points where these streamers are maintained.

The following conclusions have been made:

(1) A spark gap in series with the discharge tube affects the positive and negative corona in very characteristic and striking ways.

(2) The changes are due to intermittent currents.

(3) A hot-lime-cathode Braun tube has been developed and used in observing the weak pulsating currents which pass through the spark and the corona tube.

(4) Evidence has been given to show the relation of the corona to the arc discharge.

(5) An attempt at an explanation of the pulsating current has been made.

CHAPTER XI

Other Types of Corona Discharge

Two wires, 0.167 mm. in diameter, were arranged parallel, two centimeters apart, inside a glass tube. Photographs given in Fig. 62 were taken showing the discharge between parallel wires at reduced pressures with and without a series spark. The three lower half-tones show the typical isolated brush discharge on the negative wire with corresponding luminous sections of the positive wire. The negative brushes had a brilliant nucleus with a fainter glow spreading out from it. For pressures lower than those for which the photographs were taken, the discharge became more brilliant; the brushes spread further apart and increased in size. Each section of the positive glow was usually of uniform brilliancy. For comparatively low pressures and high voltage the positive sections became somewhat discontinuous, and bright spots mixed with the uniform glow.

Two No. 36 wires were stretched three centimeters apart over hard rubber bridges in order to be parallel and the discharge between them was studied. When the visible discharge was fairly started, it took the form of a uniform continuous glow along the negative wire. It was discovered that the humidity of the air had a marked effect upon the discharge.

The introduction of a short spark in series made a marked change in the nature of the discharge. Both wires were more or less completely covered with a nearly uniform glow and there was no longer any marked difference between positive and negative (see Fig. 62). At low pressures and relatively high voltage the discharge between the wires resembled a sheet of luminous rain. An intermediate effect had bluish streamers between the wires.

A platinum tip was arranged to be moved from one wire to the other and thus, as shown in Chapter VII, the distribution of potential between the wires was determined. Three explorations were made,—namely, when the voltages were 8,000, 10,000, and 12,000 volts.

Fig. 63 shows the curves for the field distribution and also the distribution of the field as calculated from the electrostatic formula.

The curves show that the actual distribution of the field departs widely from the electrostatic formula, especially at the lower voltages. A large anode and cathode fall of potential exists.

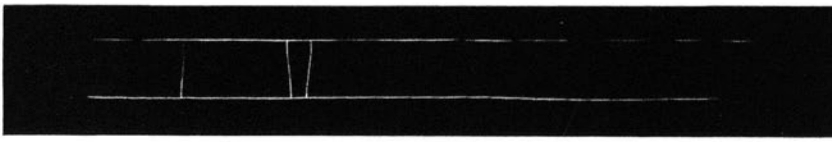
A study of the corona on a wire at the axis of a short cylinder was undertaken in order to increase the knowledge concerning the losses which occur in high voltage transformer bushings, in wall, ceiling and line insulators. For preliminary experiments it was decided to have air as the insulating medium and to use a wire passing through the axis of a short cylinder.

The apparatus consisted of an aluminum disc, 2 mm. thick, with a round hole 16 mm. in radius at its center, placed in a horizontal plane. A vertical wire passed through the center of the hole. This apparatus was enclosed in a glass jar so that dry air could be admitted.

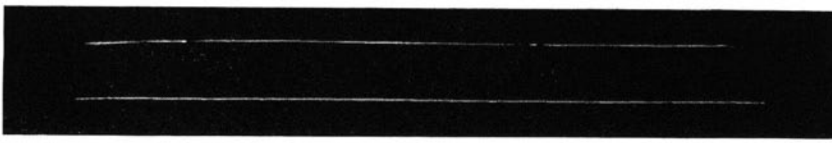
The visual phenomena of this corona depend on the polarity as in the case of coaxial cylinders, but the variety of the phenomena is even greater. If the wire is positive, the corona is uniform along the wire over a large range of voltages and pressures. Below 130 mm. of mercury pressure the typical positive glow will collapse to a much shorter and brighter glow, a few seconds after the switch is closed. After the voltage is increased, the luminous strip on the positive wire takes its final form of a triangular flag diverted toward the negative bead on the disc. With increasing voltage, the negative head on the disc becomes brighter and is accompanied by a ring of light along the edge of the disc. The colors of the positive and negative glow are distinctly different.

If the polarity is reversed, the wire becomes negative, the disc becomes positive and the positive glow, at first uniform along the edge of the disc, breaks into distinct beads. These positive beads move around the periphery of the disc, while at the same time the negative bead travels up and down along the vertical wire. This phenomenon is illustrated by Fig. 64. For higher pressures there appears a large number of negative beads on the central wire accompanied by a weak, uniform, circular, positive glow along the edge of the disc. A spark in series with this corona modifies the appearance in a way analogous to that of the coaxial cylinders.

The starting point of the corona for positive and negative wires has been observed; the results resemble those obtained in the fore-

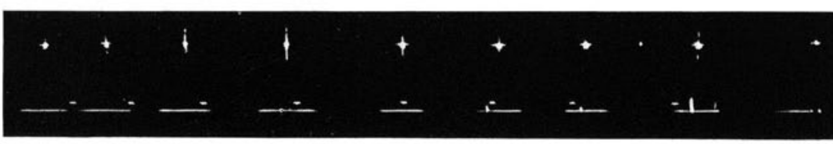


(*a*) Arc in Series, Pressure 312.2 mm., Volts 8000, Amperes 1.80×10^{-4}



(*b*) Arc in Series, Pressure 312.2 mm., Volts 8000, Amperes 1.14×10^{-4}

(*c*) No Arc, Pressure 312.2 mm., Volts 8000, Amperes 2.35×10^{-4}



(*d*) No Arc, Pressure 450.0 mm., Volts 8700

(*e*) No Arc, Pressure 450.0 mm., Volts 8400

Fig. 62. Corona between Parallel Wires at Reduced Pressures
Lower Wire is Positive in Every Case

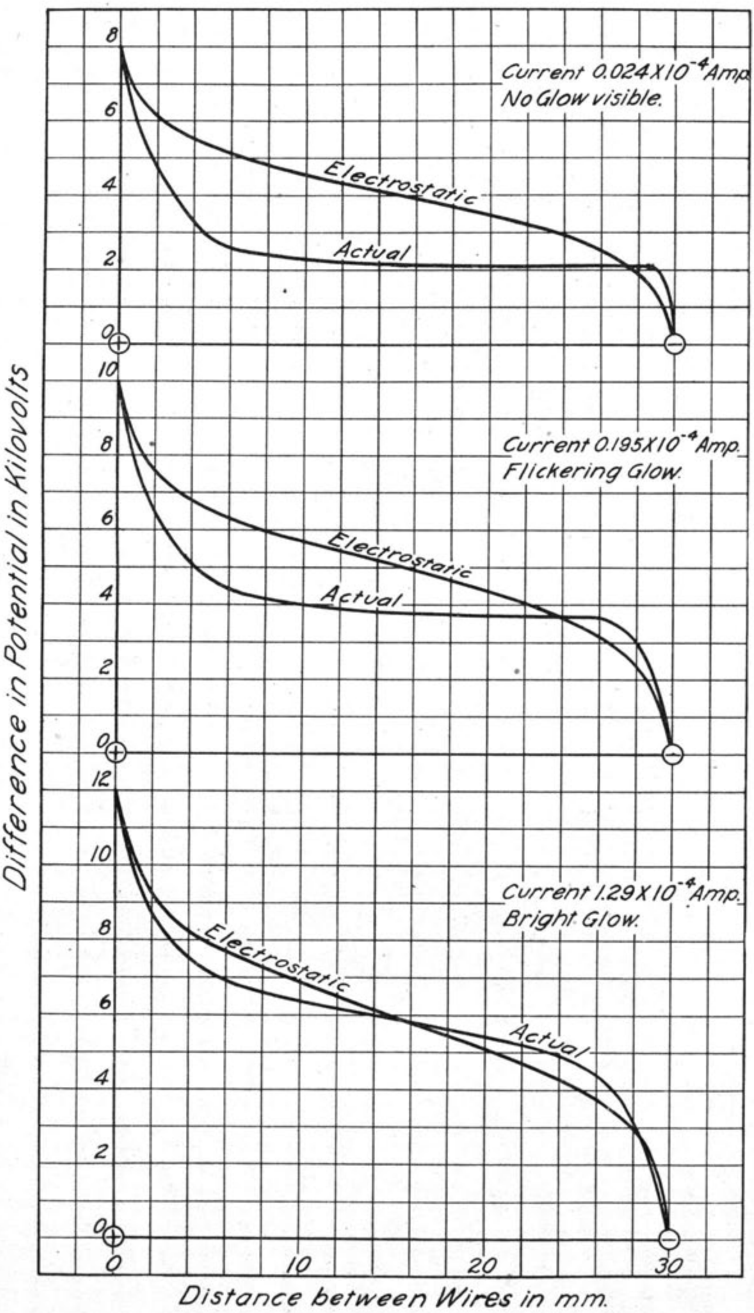


FIG. 63. FIELD DISTRIBUTION BETWEEN TWO PARALLEL 36 B. AND S. GAGE WIRES 3.0 MM. APART

going. The characteristic curves also are similar to those obtained with wire and cylinder.

The experimental knowledge of the corona is still very incomplete. Little has so far been done in the spectroscopic analysis of the various light phenomena which accompany the corona. It has been found, for instance, that the negative beads in hydrogen do not give the characteristic series lines of hydrogen, but rather a continuous band in the red and yellow region of the spectrum. It is hoped the knowledge in this field will be increased in a short time. Mechanical vibrations of the wires and an electric wind have been mentioned occasionally, but these phenomena also require further study.

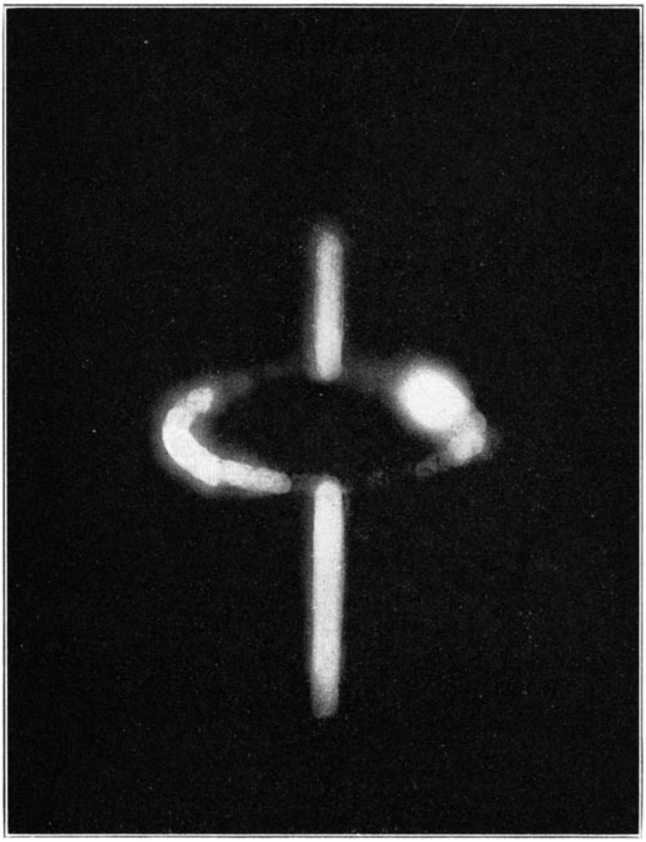


FIG. 64. CORONA ON A WIRE AT THE AXIS OF A SHORT CYLINDER

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